ARPA ORDER NO.: 189-1
7D20 Cybernetics Technology

12

AD A037493

R-1970-ARPA
February 1977

Strategic Defense Materials: A Case Study of High Temperature Engines

Richard G. Salter, Corey Dzitzer, Elwyn D. Harris,
William E. Mooz, Kathleen A. Wolf

A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

Rand
SANTA MONICA, CA. 90406

The research described in this report was sponsored by the Defense Advanced Research Projects Agency under Contract No. DAHC15-73-C-0181.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 14 R-1970-ARPA	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 Strategic Defense Materials: A Case Study of High Temperature Engines		5. TYPE OF REPORT & PERIOD COVERED 9 Interim rept.,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Richard G./Salter, Corey/Dzitzer, Elwyn D./Harris, William E./Mooz Kathleen A./Wolf		8. CONTRACT OR GRANT NUMBER(s) 15 DAHC15-73-C-0181, ARPA Order-189
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Rand Corporation 1700 Main Street Santa Monica, Ca. 90406		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency Department of Defense Arlington, VA. 22209		12. REPORT DATE 11 February 1977
		13. NUMBER OF PAGES 93
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 12 102p.		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

No restrictions

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Engines
Turbines
Materials Estimates
Chromium
Cobalt
Commodity Management
Strategic Materials
Resources

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

see reverse side

296 600

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Recent short-term commodity shortages and the potential for interruption of our supplies have caused concern that future U.S. defense systems may become increasingly dependent on materials that are potentially in short supply. This study inquires specifically into the prospects for material to be applied in the first stage turbine of man-rated military aircraft in 1990. The set of candidate material technologies that are in prospect is defined, and the component materials of these technologies that are potentially future supply problems are determined. A methodology was developed to combine the range of technology risks with the range of materials availability risks and overall comparisons were made. Due to the significant availability risks of chromium (as a necessary constituent of superalloys), ceramic materials appear to have the lowest long-term risks for high temperature engines. (Author)

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PREFACE

The United States depends upon foreign sources for a number of strategic commodities used in the production of defense systems. Interruption of these supplies could have serious repercussions for the procurement of vital weapons. The degree of seriousness depends not only on the probability of such interruptions but also on the extent to which other materials and technologies can be substituted.

This report, prepared for the Defense Advanced Research Projects Agency, examines a key defense system material requirement. A method is developed and demonstrated for jointly calculating materials availability and technological risks for alternative high temperature gas turbine engine materials.

SUMMARY

Recent short-term commodity shortages and the potential for interruption of our supplies have resulted in an increasing concern that future U.S. defense systems may become increasingly dependent upon materials that are potentially in short supply. This study for the Defense Advanced Research Projects Agency focuses on new technology demands for these potentially critical materials. The problem is to develop an understanding of the relative risks among available options, so that decisions relating to technology and/or materials selection for research and implementation can be made in a way that maximizes the probability of achieving the desired future defense capability.

The objective of the study reported here was to select a significant future material application problem and to demonstrate a quantitative procedure that can be used to make material selection decisions embodying the least risk. Two independent kinds of material risks are involved and their cumulative effects must be calculated. One is the risk of not reaching a mature state in regard to the technology of applying the material. The second is the risk of a short supply of the material itself. These risks are independent and both contribute to the uncertainty regarding a material's future utility.

A review was performed on over 500 advanced defense systems as delineated in the Advanced Technology Projections of the three services. After a number of preliminary discussions and investigations into the area of future propulsion systems, we settled on the specific question of the future prospects for materials to be applied in the first stage turbine of man-rated military aircraft. The time horizon chosen was 1990.

It was necessary to define the set of candidate material technologies that are in prospect and to determine the component materials of these technologies that are potentially future supply problems. A survey of engine developers and government research laboratories was used to develop the future performance prospects for the candidate material technologies. A survey of the literature was used to develop

the supply risks for the component materials of the candidate material technologies.

Our study shows that chromium is the only material that poses a significant availability risk to the implementation of high temperature engines for future defense systems. The technology for cooled superalloys would appear to ensure their utility at 2500°F turbine inlet temperature for man-rated military aircraft by 1990. The availability risks of chromium could reduce their probable utility for planning purposes, however, to as little as 10 percent. Metallurgical grade chromite and/or chromium metal should continue to receive the highest emphasis for U.S. stockpile inventory. Of less importance but still deserving of stockpile considerations is cobalt. Although the technology applications of columbium and tungsten are not analyzed here, their availability curves suggest that such an analysis may be appropriate. High temperature ceramic technology has the best long-term potential (lowest risk) of the technologies considered. A continuing and increasing support of R&D in ceramic turbine technology should be of high defense priority.

The methodology developed for this study allows a quantitative display of the comparative risks that exist between alternative material development strategies. This technique was found to be most useful in providing a basis for choice among complex alternative technologies, in determining which components of the overall risk are the dominant influences, and in determining the relative effects of alternative risk reducing measures. This methodology should be considered for use in R&D planning that requires comparative evaluation of alternative future technologies with complex risk patterns.

ACKNOWLEDGMENTS

We would like to express our appreciation to a number of persons who provided valuable assistance during the course of this study.

Our particular thanks go to those persons at several engine companies and in several government laboratories who gave thoughtful attention to our materials technology questionnaire. Their names are listed in Appendix B.

We would also like to express our thanks to Theodore T. Connors and Thomas F. Kirkwood for their technical review and comment on an early draft of this report.

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CONTENTS

I. INTRODUCTION

STUDY CONTEXT

Recent short-term commodity shortages and the potential for interruption of supplies of materials originating outside the United States have resulted in an increasing concern that future U.S. defense systems may be dependent upon materials of questionable availability. This study for the Defense Advanced Research Projects Agency focuses on new technology demands for these potentially unavailable materials. The problem is to compare available alternatives so that decisions relating to technology and/or materials selection for research and implementation can be made with the least risk of not achieving the desired ultimate defense capability. Our preliminary work for ARPA on this project established that there are several materials that are potentially critical in this context. It also became apparent, however, that a quantified basis for comparison was needed on which to base technology development and application decisions.

The objective of the analysis presented in this report is the selection of a significant future materials application problem and the demonstration of a methodology for determining a preferred course of action.

Our analysis is based on the premise that the selection of a material for a particular future application embodies two kinds of "risks": (1) a risk that the technology of preparing and fabricating the material in the application will not mature to a sufficient degree to insure adequate performance and reliability, and (2) a risk that the material will not be available in sufficient quantities (and at the expected prices) to satisfy the needs of the intended application. These risks are a measure of the potential uncertainty in assuring the usefulness of the application at a future point in time. For this study we have established the convention that a numeraire of 1.0 defines the case for certainty, i.e., there being 100 percent probability of achieving the desired goal (a no risk situation). A numeraire of 0 describes the case of maximum risk, i.e., zero probability of achieving the desired goal.

It is a further premise that these two kinds of risks are sufficiently independent to be combined* to derive an overall risk of achievement. That is to say, a 0.8 probability of a mature technology and a 0.8 probability of material availability will combine to a 0.64 probability of overall achievement (a 0.36 risk).

A basis for the selection of materials for a future application can now be determined as follows:

1. Candidate optional approaches for the given application can be defined.
2. An overall risk numeraire for each option can be developed using subjective estimates of material availability and technology maturity. (There can be only subjective estimates where the future is concerned.)
3. Select the option with the least overall risk (i.e., maximum probability of achieving the desired result).

FUTURE DEFENSE SYSTEMS

In order to establish a proper subject scope for the analysis reported here, a review was performed of over 500 advanced defense systems as delineated in the advanced technology projections of the three services. These systems include a gambit of weapons and support systems and advanced mission concepts. System attributes to be improved in future implementations include cost, range, weight, precision, efficiency, and survivability. Our search criteria were (1) the use of potentially critical materials, and (2) the involvement of significant quantities of such materials in the system or systems. From this review, several material application technologies were identified as candidates for further analysis. These are described in the following paragraphs.

High Temperature Applications. High temperature applications, particularly in propulsion systems, contain a number of potentially critical materials and consume a significant quantity of these materials.

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*When these risks are described as probability-density functions their combination is by iterative Monte Carlo convolution.

In addition, the technology of high temperature materials application is in a continuing state of flux with a number of alternative and substitution prospects at various stages of development. The question regarding which technologies should be pursued, and at what relative priority, hinge on a number of material development and availability uncertainties.

New Structural Materials. The use of new structural materials for moderate and ambient temperature applications also presents some interesting problems. The field of composite materials is a burgeoning area with great potential for improved strength-to-weight ratio in missile and aircraft structural systems. Although there may be some concern regarding the availability of titanium and niobium, many composite options do not appear to have materials availability problems. The nature of the problem is generally the engineering of specific applications that can be made cost competitive with more conventional alloy structures.

Superconductivity. Superconductivity is also a technology of interest and is in a developmental state of flux. It is of great interest for applications involving efficient energy transfer and for high-power-density marine propulsion systems. Material availability problems are related primarily to niobium and could be significant depending upon the rate of introduction of superconducting systems.

Solid State. A host of solid state materials and component problems are manifest in future weapon systems. These are characteristically technological research and development problems and do not appear to require raw materials in sufficient quantities to be characterized as potentially critical supply problems.

Selection of Study Topic. The scope of our study effort required the selection of a specific problem area about which to develop and demonstrate an analytical approach. Our choice was the area of high temperature materials. After a number of preliminary discussions and investigations into the area of future propulsion systems we settled on the specific question of the future use of high temperature materials in the first stage turbine of man-rated military aircraft. The time horizon chosen was 1990, and our study concerns the relative likelihood,

among the various material options that can be selected as of today, of encountering a viable situation for engine implementation in that year.

STUDY APPROACH

The measure of the criticality of a material that is potentially in short supply depends upon whether other materials or other technologies can be substituted in its various applications. For our example, it was necessary to define the set of candidate material technologies and to determine the component materials of these technologies that may have potential future supply problems. As previously stated, two kinds of risks are attendant to the choice of technologies to be pursued. One concerns the potential time schedule for the maturing of the application technology including manufacturing techniques, performance prospects, and design concepts. The other concerns the availability risks associated with the ingredient materials. Both of these risks must be included in the comparisons and quantified and combined in ways so that choices can be made.

In this study, we estimated future material availabilities and technology achievements as probability density functions. Combinations (convolution) of these functions were made using a Monte Carlo computer model.

Section II of this report describes the approach we used to obtain quantified risk data for the key technologies involved. In order to accomplish this task, we interrogated the industrial expertise at gas turbine engine manufacturers and the research expertise resident in several government laboratories with a questionnaire* that was designed to yield quantifiable estimates.

Section III of this report covers the process that we used to estimate material availability. Since there was already a host of materials availability data (see the references in Appendix D), we chose to draw upon these data and interpret them with our own project team.

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*The questionnaire, a listing of respondents, and the responses are given in Appendixes A, B, and C, respectively.

Section IV synthesizes the risks for each option in order to make relative comparisons among the alternatives from which to draw conclusions.

Section V lists the conclusions that may be reached from this study.

II. MATERIALS TECHNOLOGY

The requirements of future weapons systems for new materials was reviewed with various service organizations and material laboratories. In this review, we concentrated on *new* material requirements to avoid duplication of the Stanford Research Institute study of current aggregate DoD material requirements. For the Air Force, this review included ramjets, rocket engines, strategic and tactical missiles, gas turbine engines, space propulsion, and aircraft structures. For the Army, the review included gas turbine engines, gear boxes, transmissions, rotor blades, armor, and structural materials. For the Navy, we concentrated only on the components of nonnuclear marine propulsion systems and, especially, on the naval gas turbine program. In addition to these programs, we also examined the ceramic gas turbine and the segmented magnet homopolar generator/motor research programs being supported by ARPA.

Although we found that a number of new materials are expected to be required by the services as a result of the application of advanced propulsion systems to weapon systems, we found that: (1) for the most part, the DoD demand for materials having a supply risk would be very small in comparison with the overall U.S. demand; (2) the trend is toward the use of composite materials having very little supply risk; and (3) the material requirements of new weapon systems were largely those of past systems. An exception to the above was the gas turbine engine for man-rated systems. Not only does this program involve fairly large quantities of materials, but the direction is toward the use of more exotic technology in the high temperature turbine section in order to allow operation with higher turbine inlet temperatures. While all of these technologies do not involve critical supply risks, they do involve (to a varying degree) technology risks associated with the achievement to a specified turbine inlet temperature within a given time frame.

At this point, we decided to narrow the study effort to the materials being developed for the first stage turbine nozzle diaphragm

and rotating wheel in advanced man-rated military aircraft, circa 1990 implementation. This focus reduced the data collection task while embodying the salient technologies to be analyzed. The material technologies that were distilled from our earlier discussions include the following: superalloys, superalloys with cooling and coating techniques, coated refractories, oxide dispersions, directionally solidified superalloys, directionally solidified eutectics, ceramic composites, and ceramics. The distinctions between these categories of materials is somewhat arbitrary, but fairly well understood among those in the industry. Superalloys are currently employed in all working gas turbine engines, usually in conjunction with turbine cooling. The balance of the materials noted are all in active development but at varying states of maturity.

We then formulated an approach to deriving a relative risk among the use of these technologies for the 1990 time frame. Although considerable reference material is available from which to draw these conclusions (see Refs. 1-3), it was decided to augment these data with a current survey of engine developers and government research laboratories. The problem was to formulate a questionnaire that could be used to assess this expertise, thus providing a quantified response, but with the option to qualify the estimated numbers. A questionnaire was developed and tested within The Rand Corporation staff and is included here as Appendix A. It asked for a quantifying estimate (for each of the material technologies listed a most pessimistic, an expected, and most optimistic estimation) of the turbine inlet temperature limit at which these technologies could be employed in the year 1990. Estimates were requested for the first stage nozzle diaphragm as well as the first stage turbine blades of a military man-rated engine. Qualifying comments were elicited relating to (a) specific material property limits imbedded in their estimates, (b) the role of fabricating techniques important to their estimates, (c) special design concepts that are necessary to their estimates, and (d) the extent to which a reallocation of R&D funding might shift the estimation pattern they present. These questionnaires were submitted to the industrial concerns and the government laboratories with varying degrees of preliminary conversations

and explanations. The organizations and persons who responded are listed in Appendix B and their responses are presented in Appendix C as received, but without attribution. The reasons for this is that roughly half of the respondents preferred to remain anonymous with regard to their specific commentary.

Figure 1 describes the distribution of responses to the questionnaire for three material technology categories. The distributions shown were developed from averages of the expected, pessimistic, and optmistic estimates for these categories. The narrowest distribution is for superalloys. Adding cooling and coating techniques broadened the distribution because of the increasing uncertainties in performance potential and because of the variation in the extent of cooling that is deemed useful from a cycle efficiency point of view.

The ceramics distribution is the broadest of all, since greater uncertainty exists as to its performance capability. There was also concern expressed in two of the responses that the minimum reliability

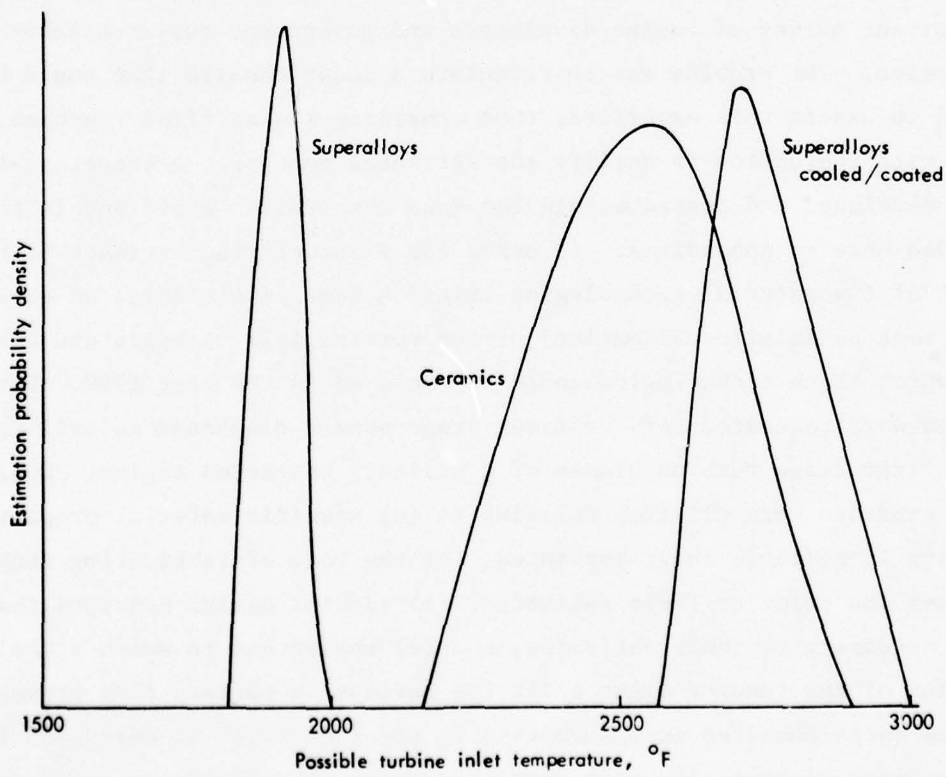

Fig. 1 — Material technology projections circa 1990

required for man-rated aircraft use would not be achieved with ceramics. In one case, no possibility of such use was projected and in another, this outcome was projected only in the pessimistic case.

Concern was also expressed about the continued application of superalloys in gas environments that exceed their melting temperature by relying on complicated cooling techniques. It was noted that the confidence in such mechanically cooled systems represents a barrier that any new material must overcome before it can substantially replace superalloys in these high temperature applications.

III. MATERIAL AVAILABILITY

The price coupling of supply and demand assures that in the marketplace an equality will exist. This equality will be maintained over time; as demand grows, the supply will grow, both being affected by the availability of resources, profit potential, etc. Technology commitments to specific materials for weapon systems are made based on assumed prospects for a smooth and gradual change in availability of materials and of the prices of materials. These commitments include product designs and manufacturing tooling implementations. Characteristically, the life cycle of a DoD weapon system is measured in terms of years during which time replacement parts are continually needed to maintain force effectiveness.

Our concern here is for the transient problems resulting from short-term perturbations in material supply or demand. The range of concern is for perturbations having time constants of up to, say, five years, which can cause difficulties in the continuum of product production rates. The risk of such perturbations forms the basis for the analytical metrics employed here.

The material technologies associated with the alternative means of achieving higher turbine inlet temperatures, described in Sec. II, were examined for basic mineral components for which supply concerns in the 1990 time frame may exist. Ten materials were isolated for further study as shown in Table 1. The most recent data available are compiled on separate data sheets for each of these metals (see Appendix D for supply/demand data sheets and sources). The metal-data sheets are

Table 1

POTENTIALLY CRITICAL MATERIALS

Chromium, Cr	Tungsten, W
Cobalt, Co	Hafnium, Hf
Nickel, Ni	Tantulum, Ta
Columbium (Niobium), Cb	Thorium, Th
Titanium, Ti	Zirconium, Zr

organized to provide data associated with three risk categories: The first risk category accounts for the supply as it may be affected by the world production capacity and international distribution patterns. It includes data on reserves, mine and refinery production, consumption, technological advances, capital investment problems, and environmental constraints. The second category accounts for the supply as it may be influenced by an interruption of U.S. access to the world production. This category describes sources of U.S. imports that can be interpreted in terms of prospects for cartels and embargoes. The third category is concerned with future U.S. demand and incorporates information on new uses, functional and material substitutions, end uses, recycling, the average annual growth in U.S. primary mineral demand, and DoD consumption.

ESTIMATION OF SUPPLY AND DEMAND RISKS

Scale for Numerical Estimates

Risk values have been generated by the project team in joint deliberation based on the chance of a deviation above or below the matched supply demand projection curves, at the projected time period, for each of the three risk categories. These results are presented in Table 2. A value less than 1.00 indicates the extent of the possible undersupply (or reduced demand), e.g., a 0.75 supply numeric implies a 25 percent smaller supply than anticipated. A value greater than 1.00 represents the possible oversupply (or increased demand), e.g., a 1.05 numeric implies a 5 percent oversupply.

The *expected* risk refers to the most probable condition, that is, the extent to which the supply or demand situation is *likely* to deviate from a matched supply/demand projection. The *maximum* and *minimum* risks represent the "worst case" conditions, that is, the lowest and the highest possible deviation from the matched supply/demand projection curve.

Typical Factors Incorporated in Estimates

United States and friendly reserves of chromium are negligible, domestic mine production has ceased, and domestic refining capacity is

Table 2

MATERIALS SUPPLY AND DEMAND RISK ANALYSIS

Metal (Risk Category)	Minimum	Expected	Maximum
Cr			
1[a]	.75	.95	1.05
2[b]	.65	.80	1.00
3[c]	.80	1.00	1.25
Co			
1	.75	.95	1.05
2	.75	.85	1.00
3	.85	1.00	1.15
Ni			
1	.95	.99	1.10
2	.95	1.00	1.00
3	.85	1.00	1.10
Cb			
1	.85	.98	1.05
2	.80	.90	1.00
3	.85	1.00	1.30
Ti			
1	.95	.99	1.10
2	.95	1.00	1.00
3	.85	1.00	1.10
W			
1	.75	.95	1.05
2	.85	.95	1.00
3	.90	1.00	1.10
Hf			
1	.95	.99	1.10
2	.95	1.00	1.00
3	.65	1.00	1.10
Ta			
1	.85	.98	1.05
2	.90	.95	1.00
3	.85	1.00	1.10
Th			
1	.98	1.00	1.10
2	.98	1.00	1.00
3	.85	1.00	1.10
Zr			
1	.95	.99	1.10
2	.95	1.00	1.00
3	.90	1.00	1.15

NOTE: The value 1.00 represents a match of supply and demand.

[a]World production capacity and international distribution pattern.

[b]U.S. material supply access as it may be influenced by economic or political interruptions.

[c]Material demand.

declining. Imports are primarily from the USSR, South Africa, and Rhodesia. In the third world countries there is a high probability of internal strife, which could reduce production. Soviet reserves are being reduced rapidly, which could cause a reduced supply by 1990; U.S. political relations with the USSR and Rhodesia are such that an interruption of the supply from these sources is possible. The demand projection for chromium is likely to be relatively stable. Stainless steels and superalloys require chromium. New uses might be expected to offset most other areas where other materials can be substituted for chromium.

Cobalt and tungsten also have high supply risks. We are almost completely dependent upon imports of cobalt because of negligible domestic reserves and no mine production. Although we presently produce about half of our tungsten consumption, the projected U.S. production/demand ratio for tungsten also approaches zero and "friendly" reserves are low. The case for cobalt parallels that for chromium, Zaire having a high potential for internal political conflict with an attendant prospect for reduced production. Increasing capital investment costs could also adversely affect cobalt production.

In the case of columbium and tantalum, we lack domestic reserves and mine production. Economic deposits of tantalum are relatively scarce throughout the world. Columbium imports arrive almost exclusively from Brazil, which has two-thirds of the world reserves and produces more than half the world's supply. However, the supply risk is smaller for columbium and tantalum than for chromium and cobalt. In the case for columbium, this is accounted for by the relatively high (9 percent per year) world production growth rate, the large reserve capacity, and the apparent decrease in U.S. consumption as compared to world production. In the case for tantalum, the risk is reduced, because of the relative internal stability of the two major importers, Australia and Canada.

Nickel and titanium have been assigned relatively small supply risks. We have ample friendly reserves and an availability of domestic mine production and refining industry. Our nickel refinery capacity is expanding. New mining techniques, the exploitation of lateritic ores,

the expansion of International Nickel Company in friendly countries, and the certain ability to decrease U.S. import dependence if nickel prices rise significantly imply a low supply risk as does the fact that Canada is likely to remain the major supplier. Some supply risk might be incurred by constraints related to open pit laterite mining. In the case of titanium, the world, including the United States, has excess refinery capacity. Technological advances, e.g., synthetic rutile production, would make available large illmenite reserves for titanium production. The already large reserve-to-production ratio and the internal stability of our major suppliers, Japan and Australia, also reduce the supply risk. Here, again, environmental constraints could impose some supply risk.

Hafnium has a potential for low demand because of the lack of commercial uses and the existence of alternative materials for its main application in nuclear reactors. However, if the demand for reactor-grade hafnium continues and there is no economic and/or technical provocation to utilize substitutions, then the demand would be expected to follow the anticipated curve.

On the other hand, the demand for zirconium and tungsten should hold up. Substitutions can be utilized in specialty steel and in wear-resistant applications, which pertain to the major end uses of tungsten and in foundries, refractories, ceramics and alloys for zirconium. However, additional nuclear reactor and carbide usage for tungsten and additional nuclear power, construction, superconductivity, and fuel cell applications for zirconium are projected. The negative effect upon demand anticipated from substitutions is reduced by the positive effect upon demand by the high prospect of these additional uses.

Columbium, being a necessary ingredient in most superconductors without substitution possibilities, has the highest prospect for increased demand, primarily because of the very large prospects of growth in demand for superconductors, plus other important applications. The case for columbium demand contrasts with the cases for tantalum and titanium. If tantalum prices are substantially increased, demand will decrease owing to the numerous substitution possibilities. Many substitution possibilities exist for titanium in its main applications.

Furthermore, the likelihood of a maximum demand for the two metals would tend to be reduced by good recycling possibilities. Technological improvement in tantalum scrap recovery could result in an increasingly important supply source, thereby reducing our demand from foreign sources. Secondary source recovery from titanium already provides a relatively large percentage of U.S. demand.

CALCULATION OF AVAILABILITY RISKS

A combined metric for describing the integrated risk of availability is defined as the ratio of the supply and demand risks. Thus, the availability risks for a given material are given by a convolution* of the distributions listed in Table 2.

$$R_A = \frac{[\text{Basic World Supply/Production}][\text{Interruption of U.S. Access to World Supplies}]}{[\text{U.S. Demand}]}$$

where R_A is the availability risk of a given material, considering all of the supply and demand risks involved.

The results of these convolutions are shown in Figs. 2, 3, and 4. Figure 2 shows the principal alloying components of unique importance to superalloys. Figure 3 shows three materials of moderate significance in superalloys, in lightweight alloys, and in superconductors. Figure 4 shows four metals of noncritical significance in high temperature alloys. The interpretation of these curves is discussed by reference to Fig. 2. In the case of nickel, the curve shows that the expected availability of this commodity across the various applications in the U.S. economy is unity. That is, the growth of supply and demand is expected to be well matched and in the year 1990 an over or under supply is not expected. The nickel curve also suggests that of the many possible perturbations in either supply or demand the combined effects could be no more significant than to cause a 12 percent shortfall or a 23 percent oversupply. In the case of cobalt, however, it is expected that supply and/or demand

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*The multiplication/division of distributed variables using an iterative Monte Carlo model. In this case, the *minimum*, *expected*, and *maximum* values for each variable are interpreted as the parameters of a beta distribution.

perturbations circa 1990 will result in a 20 percent shortfall. The reader is reminded that these metrics derive from the subjective estimates of the project team.

It should be remembered that interpretation of these curves may be more pertinent in the relative sense rather than in absolute terms. The estimation of subjective probabilities regarding future events may be assumed to be consistent among a number of alternatives even though all estimates may be biased on an absolute scale.

The implications of these risks are discussed in Sec. V.

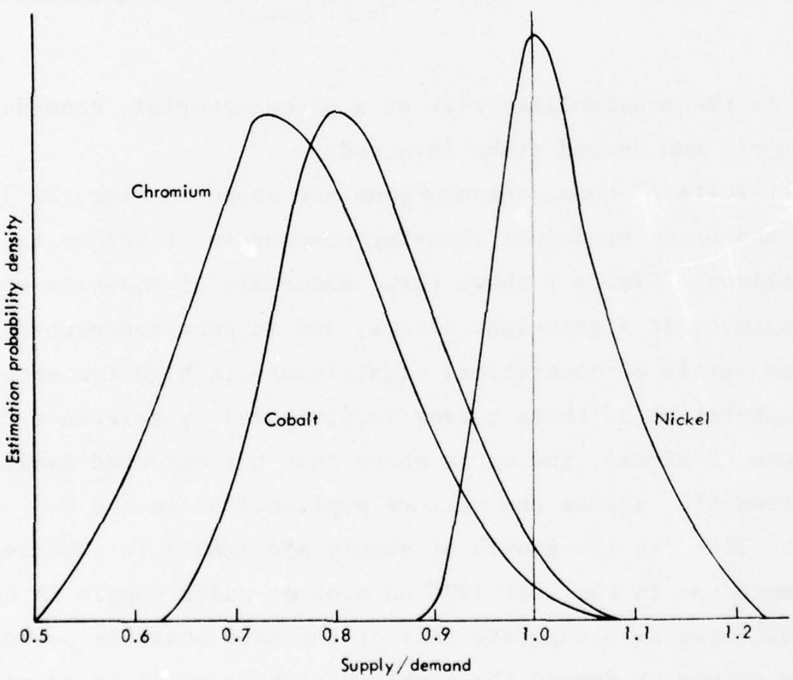

Fig. 2—Material availability risks in 1990: chromium, cobalt, and nickel

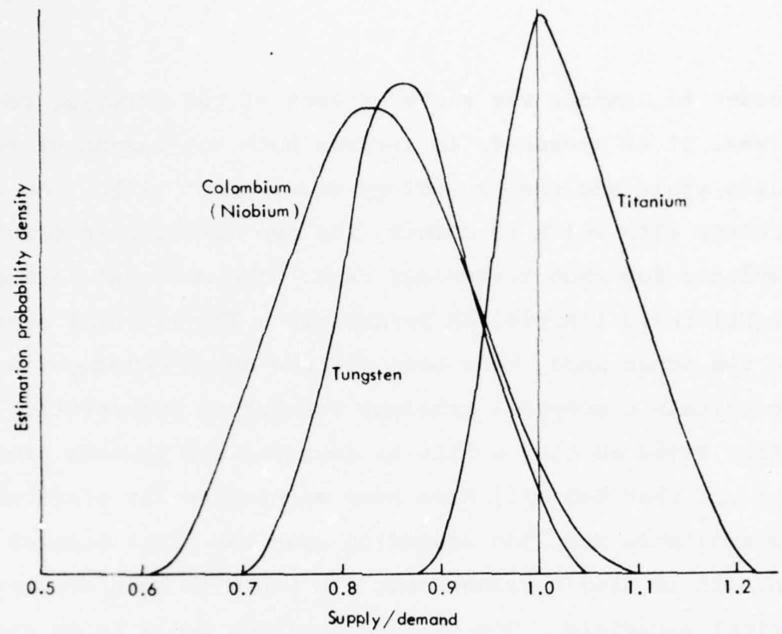

Fig. 3—Material availability risks in 1990: colombium, tungsten, and titanium

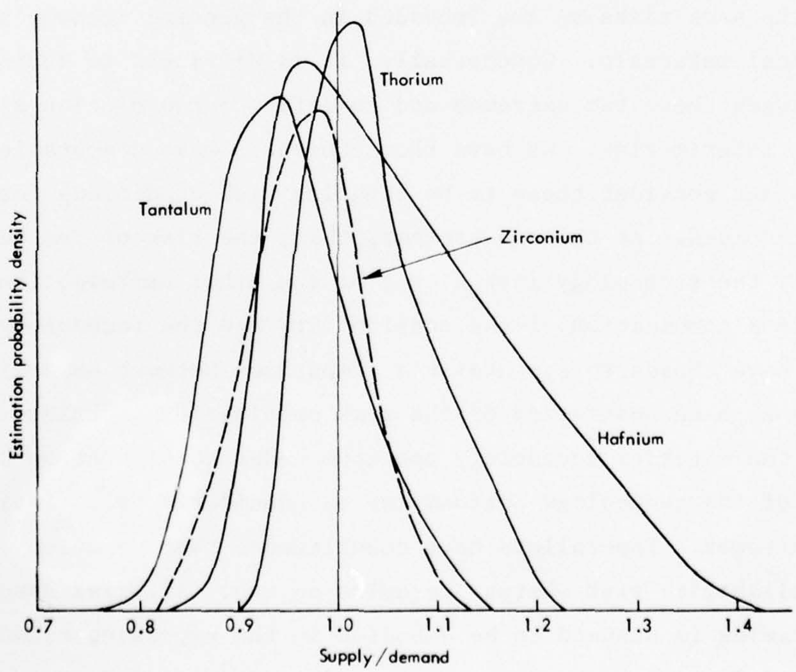

Fig. 4—Material availability risks in 1990: tantalum, thorium, zirconium, and hafnium

IV. COMBINED RISKS

In order to compare the risks of each of the material technology alternatives, it is necessary to include both the component materials availability risks and the technology development risks. An algorithm must be chosen with which to combine the two distributed risks parameters developed for each technology case. The material technology risks are straightforward distributed parameters. The material availability risks, on the other hand, have been defined on an economy-wide basis. There are certain conceptual problems related to interpreting these availability risks as they relate to advanced DoD systems production. It is apparent that DoD will have some mechanisms for preferential access to available supplies depending upon the circumstances of the situation. It is also apparent that the DoD will have stockpiles of most critical materials. One extreme position would be to assume that due to these factors the DoD does not have material risks provided they have planned the mechanisms and the stockpile sizes properly. The other extreme is to assume that the DoD production processes have approximately the same risks as are imbedded in the general economy's access to critical materials. Conceptually, it is difficult to define a DoD risk between these two extremes and to define a convolution algorithm for this interim risk. We have thus chosen to make computations at the extremes and consider these to be bounding risk conditions for the technology involved. At the one extreme, then, the risk of the technology is simply the technology risk alone; at the other extreme, the risk simply is a combination of the availability and the technology risks.

We have chosen to synthesize a comparison between superalloys and ceramics as a demonstration of the risk combination technique at the two ends of the material technology spectrum under consideration here. The balance of the technology options can be considered as variations between these extremes. Superalloys have constituents that represent a bona fide availability risk whereas ceramics do not. All risk associated with ceramics is assumed to be embodied in the expressed technical risks as derived from our source data. A review of the components of the family of superalloys suggests the following:

1. Chromium is a necessity to all members of the family because of its high temperature corrosion characteristics.
2. Either nickel or cobalt is required to compound superalloys.
3. The remaining alloying constituents are numerous and highly substitutable and do not contribute significantly to availability risk.

We have, therefore, defined an availability algorithm to be used in computing the availability of superalloys as follows:

$$
\begin{aligned}
\text{Avail}_{Sa} &= \text{Avail}_{Cr} \times \text{Joint Avail}_{Ni|Co} \\
&= \text{Avail}_{Cr}\ (1 - \text{Joint Risk}_{Ni|Co}) \\
&= \text{Avail}_{Cr}\ (1 - R_{Ni}\ R_{Co}) \\
&= \text{Avail}_{Cr}\ [1 - (1 - A_{Ni})(1 - A_{Co})] \\
&= \text{Avail}_{Cr}\ (A_{Ni} + A_{Co} - A_{Ni}A_{Co})
\end{aligned}
$$

The availability distributions of the constituents of superalloys are shown in Fig. 2 of the previous section. The results of this convolution are shown in Fig. 5. It can be observed that the result is very similar to the curve for chromium, since the joint risk for cobalt and nickel contributes little increased risk of compounding superalloys because of the high availability of nickel.

The combined risk of three basic material technologies is examined for their relative potential utility as a function of desired turbine inlet temperature. They are superalloys, superalloys with cooling and/or coating, and ceramics. Curves 2, 4, and 5 of Fig. 6 show the probability of material utility (1-Combined Risks) as a function of desired turbine inlet temperature at the extreme assumption that availability of constituents does not contribute additional risk. If we add the risk of material availability the superalloy curves 2 and 4 move to positions 1 and 3, respectively. The differences between curves 1 and 2 and between 3 and 4 represent the extreme positions depending upon

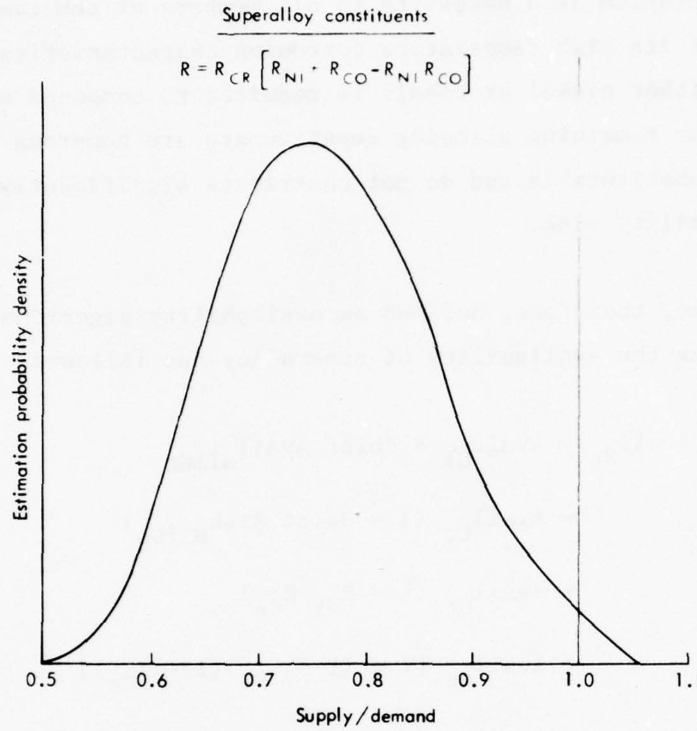

Fig. 5—Material availability risks in 1990

one's assumption of the impact of material availability risk to superalloys. As previously noted, no availability risks are pertinent to the ceramic curve.

The application of the data presented in Fig. 6 might be visualized in the context of the choices presented to an advanced engine program planner in 1976, whose engine is to be used in a new application in 1990. Let us assume that system and engine cycle design results suggest the desirability of an average turbine inlet gas temperature of 2500°F. It is apparent that superalloys without cooling will not be adequate, so let us further assume that cycle performance and reliability criteria would tolerate the use of cooling and coating to allow the employment of superalloys at the desired temperature. It would be apparent then from the position of curves 4 and 5 that, technically, either superalloys with cooling or ceramics show a high probability of being employable at 2500°F turbine inlet temperature.

Curve no.	1	2	3	4	5
Superalloys	*	*	*	*	
Ceramics					*
With availability risks	*		*		
With cooling and/ or coatings			*	*	

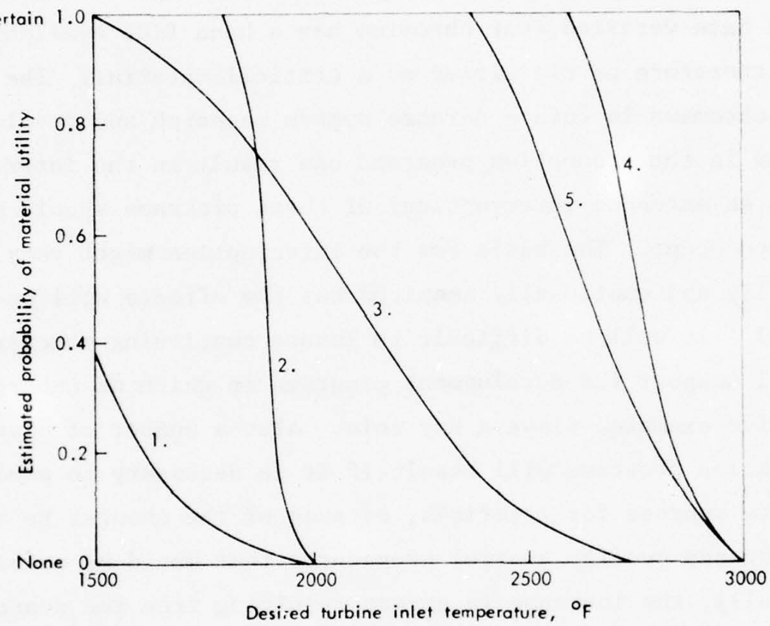

Fig. 6—Estimated relative utility of alternative material technologies circa 1990

However, if the strategic availability of materials is to be considered in the system program planning, it is apparent from the position of curve 3 that this criterion can reduce the probable utility of cooled superalloys by a significant factor. In fact, if the availability risk to the general economy is assumed, the probable utility is reduced to only 10 percent. The actual numerics here should be interpreted in terms of the order of magnitude of the leverage that availability can exert. Other subjective factors will be involved in choosing, for a given application, the extent to which availability risks approach those implied by the position of curve 3. However, it is apparent that thoughtful program plans should be based, to the extent possible, on a quantified display of the inherent risks.

V. CONCLUSIONS

THE IMPLICATIONS OF CHROMIUM SUPPLY RISK

In our case study of high temperature gas turbine engines circa 1990, we have verified that chromium has a bona fide availability risk and can therefore be classified as a critical material. The employment of chromium in future defense system research and development programs and in the production programs can result in the interruption (perhaps an extended interruption) of these programs should a supply disruption occur. The basis for the interruption might very well be politically and emotionally inspired but the effects will be nonetheless real. It will be difficult to insure continuing monetary and political support for development programs in which an embargoed material, for example, plays a key role. Also a number of disruptions to production programs will result if it is necessary to mobilize substitute sources for materials, because of the changes to material processing and quality control procedures that would be necessary. And, finally, the increase in prices resulting from the scarcities can have a significant effect on budget allocations for defense systems.

In the case of the chromium supply problem, it is suggested that:

- A continuing review of chromium stockpile objectives be conducted to insure an adequate supply for at least a year's defense production needs.
- Materials R&D emphasize the development of substitute for chromium uses wherever possible.

SUBSTITUTE HIGH TEMPERATURE TECHNOLOGY

High temperature ceramic technology has the best long-term potential (lowest risk) of the candidate technologies considered as alternatives to chromium based superalloys. A continuing and increasing support of R&D in ceramic turbine technology should be of high defense priority. As one researcher put it--time is needed to both develop and demonstrate the material utility and to build confidence

in the use of brittle materials in this hazardous environment. A concensus of the high temperature materials research and development community (see Appendix C) suggests that funding of ceramics research should be increased over the aggregate of current levels by $10 million to $60 million over the next 15 years. To the extent that ARPA's ceramic research program in the automotive turbine field reaches its objectives and is diminished in scope or terminated, other DoD agencies should be encouraged to increase their participation proportionally. The R&D program should include work on a range of problems relating to ceramic material properties (fracture toughness, impact resistance), fabrication techniques (net shape production techniques), and design concepts (ceramic/metal attachments).

OTHER POTENTIALLY CRITICAL MATERIALS

Over and above the demonstrated criticality of chromium, three other materials appear to have at least a potential status as critical materials. These are cobalt, columbium, and tungsten. They are not critical in high temperature engine applications but actually may be critical because of limited substitutability in other applications such as superconducting systems and lightweight structures. It is recommended that ARPA support an analysis to determine the degree of material and/or technological substitutability for these materials across the range of possible future uses. Even though one ingredient of the criticality is established in our study, an actual critical status cannot be determined without this broader applications analysis.

FURTHER APPLICATION OF THE METHODOLOGY

The techniques used in this study allow a quantitative comparison of the risks that exist between alternative material development strategies. The example that was chosen pertained to the gas turbine, but the technique can, and perhaps should, be used in other areas where technological and availability risks coexist. One of the findings of this study was that most advanced technologies involve the use of uncommon materials, and this will probably become more pronounced in the future. Choices between technologies should incorporate a careful

assessment of the materials involved, and the resulting combined risks. The method used in this study can contribute substantially to an understanding of these risks.

Appendix A

MATERIAL TECHNOLOGY QUESTIONNAIRE

INTRODUCTION

The Rand Corporation is conducting an assessment for the Defense Advanced Research Projects Agency (ARPA) of the future performance prospects of alternative high temperature material technologies as applied to gas turbine engines used in manned military aircraft.

For purposes of this assessment, we have chosen to focus on the first stage of the turbine as the component which largely determines the maximum cycle temperature capability of the engine. We are attempting to determine a means of estimating the probability of reaching improved temperature capabilities in gas turbines at a specified future time.* Each alternative must be comparable in terms of operational considerations such as maintenance and reliability.

This questionnaire is in three parts. In Part 1, we ask for your estimates of Turbine Inlet Gas Temperature for several material technologies. In Part 2, we ask for background information underlying the estimates given in Part 1. Part 3 consists of several administrative questions.

---

*We recognize that actual application considerations may dictate the use of a turbine inlet temperature below the maximum capability provided by materials technology.

PART 1

OVERALL ESTIMATES

In Tables 1 and 2 we would like you to fill in your best estimates of the Turbine Inlet Gas Temperature limits appropriate to each material technology. We are asking for your most pessimistic estimate, your most optimistic estimate and your nominal expectation assuming in this latter case a most likely level of R&D funding support. It is to be assumed that the application of the material is for the first stage turbine blades and for the nozzle diaphragm; we would like your estimates for both components.

Your temperature estimate should assume in each case that the particular material technology and design technique for a component are the only limitation on the engine average turbine inlet gas temperature. For example, an "expected" estimate of 3000°F for a ceramic nozzle diaphragm might be made even though you feel that no material will achieve that level of performance in the rotating stage.

Although our intent is to focus on those material technologies listed in Tables 1 and 2 as the primary candidates for increasing the turbine inlet gas temperature of gas turbine engines, we recognize that this list is not necessarily all-inclusive and that other classes of materials are candidates; please add those materials that you consider should be included.

Estimator's Name ____________________

Organization ____________________

Table 1

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE NOZZLE DIAPHRAGM

	Estimated Capability Turbine Inlet Gas Temperature, °F		
Material Technologies	Pessimistic	Expected	Optimistic
1. Superalloys			
2. Superalloys with Cooling			
3. Coated Refractories			
4. Oxide Dispersions			
5. Directionally Solidified Superalloys			
6. Directionally Solidified Eutectics			
7. Ceramic Composites			
8. Ceramics			
(Other)			

Estimator's Name____________

Organization____________

Table 2

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)
APPLICATION: FIRST STAGE TURBINE BLADES

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F		
	Pessimistic	Expected	Optimistic
1. Superalloys			
2. Superalloys with Cooling			
3. Coated Refractories			
4. Oxide Dispersions			
5. Directionally Solidified Superalloys			
6. Directionally Solidified Eutectics			
7. Ceramic Composites			
8. Ceramics			
(Other)			

PART 2

Making the estimates for Part 1 required implicit assumptions regarding the progress of a number of influencing factors in the material application technology. The purpose of this part of the questionnaire is to provide you an opportunity to make explicit some of these assumptions. Where appropriate, please provide any qualifying statements that would clarify the basis for your answer.

QUESTION A

Oftentimes a specific material property limits its application, and if this particular property can be improved through research, the material can then be used in more advanced applications. In your estimate of turbine inlet temperatures for the various classes of materials, you assumed advances in certain physical, structural, chemical, or thermal properties. Please list the more important developments that are required for each material technology and indicate whether these efforts are supported by R&D funding at a sufficient level to bring your estimates to fruition. If not, what additional support is required?

QUESTION B

In some cases current fabricating techniques may be inadequate or inappropriate for new material technologies. In your opinion, would fabrication developments be required to support your material capability estimates given in Part 1? Important fabrication technologies might include hot die forging, diffusion bonding, solidification techniques, powdered metallurgy, etc.

QUESTION C

Describe any special design concepts which you have assumed in your temperature estimates in Part 1. Would these concepts require a development effort not currently contemplated and/or funded?

QUESTION D

Your estimates in Part 1 were based, among other things, on the availability of likely R&D funding. Here we would like to obtain your opinion of the sensitivity of those estimates to a shift in research priorities. Can you identify any specific changes or additions to R&D fund allocations which would significantly change your estimates given in Part 1, for example, convert your "optimistic" estimate to an "expected" result.

PART 3

ADMINISTRATION QUESTIONS

1. Do you consider yourself an expert in gas turbine engines:

	Yes	No
a. Design	_____	_____
b. Materials	_____	_____
c. Development	_____	_____
d. Overall	_____	_____

2. Is your expertise limited to one particular material technology or engine component:

   No _____

   Yes _____

   If yes, which one ____________________

3. Would you like to obtain feedback from this questionnaire?

   No _____

   Yes _____

4. May we attribute these estimates to you?

   No _____

   Yes _____

   Signature____________________________

Appendix B

RESPONDENTS TO QUESTIONNAIRE

1. The General Electric Company, Aircraft Engine Group, Cincinnati, Ohio, Dr. Shirley Wakefield (a joint response).
2. National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, James R. Johnson and R. L. Ashbrook.
3. Pratt and Whitney Aircraft, Florida Research and Development Center, West Palm Beach, Florida, G. F. Calvert (a joint response).
4. Rolls-Royce (1971) Ltd., Derby Engine Division, Derby, England, L. G. Dawson (a joint response).
5. U.S. Air Force Advanced Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, E. C. Simpson.
6. U.S. Army Aviation Materials Research and Development Laboratory, Ft. Eustis, Virginia, Graydon A. Elliott.
7. U.S. Army Materials and Mechanics Research Center, Watertown, Mass.
   - A. R. D. French
   - B. R. N. Katz.

Appendix C

QUESTIONNAIRE RESPONSES

This appendix reproduces the substantive parts of the responses to the High Temperature Materials Technology Questionnaire. (Because a number of respondents indicated that they did not want their estimates attributed to them, it was necessary to sanitize the responses so that the source could not be determined.) Eight responses were received and are presented here in an order determined by the estimate of expected superalloy turbine inlet temperature.

The responses are presented here exactly as received--except for letterhead identifications, but including handwritten insertions and marginal comments--to preserve important qualifying remarks.

(RESPONSE A)

Table 1

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE NOZZLE DIAPHRAGM

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F Pessimistic	Expected	Optimistic
1. Superalloys	1600°	1750°	1850°
2. Superalloys with Cooling	1850°	2300°	2350°
3. Coated Refractories	2000° 2300°	2300° 2700°	2500° uncooled 3000° cooled *
4. Oxide Dispersions	2000°	2300°	2500°
5. Directionally Solidified Superalloys	2100°	2350°	2400°
6. Directionally Solidified Eutectics	2100°	2500°	2550°
7. Ceramic Composites	2000°	2500°	3000°
8. Ceramics	2000°	2500°	3000°
(Other)			

* but without cooling some refractories will burn freely at this temperature

Table 2

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE TURBINE BLADES

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F * Pessimistic	Expected	Optimistic
1. Superalloys	1600°	1750°	1850°
2. Superalloys with Cooling	1850°	2300°	2350°
3. Coated Refractories	2000°	2200°	2500°
4. Oxide Dispersions	2000	2100°	2300°
5. Directionally Solidified Superalloys	2100°	2350°	2400°
6. Directionally Solidified Eutectics	2100°	2500°	2550°
7. Ceramic Composites	2000°	2500°	3000°
8. Ceramics	2000°	2500°	3000°
(Other)			

* This temperature is assumed to be measured at the nozzle and not at the first gas generator rotor.

Answer to Question A:

Superalloys:

a. Cobalt-base superalloys do not have the strength of the nickel-base superalloys and are therefore not in contention for use in rotating parts at peak temperatures. Work has been underway for many years to develop a strengthening precipitate analogous to Ni_3X. This work is not strongly financed since other approaches seem to offer earlier rewards.

b. The upper limit on the use of nickel-base superalloys is limited only by a willingness to operate with a gas temperature equal to or greater than the incipient melting point of the metal. All of the superalloys are eutectics with an incipient melting point below 2575°F. Further return from R&D is doubtful.

c. Dispersion strengthened superalloys do not have the potential of directionally solidified entectics. Return from further R&D not expected to be significant for strength improvements but will help corrosion resistance.

Refractory Alloys:

Columbium alloys offer the only reasonable opportunity in this category. Principal shortcoming is embrittlement due to oxidation in the service temperature range. For small engines the best approach to manufacturing refractory metal nozzles and blades is casting. Most available columbium alloys were designed for use in a wrought form. For nozzle applications, some of the available alloys have adequate properties in the as-cast condition. Rotating components, however, require the development of a higher strength casting alloy having at least 5% ductility (tensile elongation).

Additional Note on Metals:

There are two additional problems to be faced with metals. First, and most important, better coatings, coating application, coating stripping, and coating inspection techniques are needed. None of the metals noted above will survive for any reasonable length of time in their working environment today without a coating. This is where the R&D dollars would be most beneficial.

The second problem has become critical for directionally solidified superalloys but is a point for consideration with the others; this is the repair problem. Whether by alloy or component design, the end products have become so sophisticated that normal repair procedures do no apply. Yet the price per blade is so high that the question of acquisition and life cycle affordability is paramount. Therefore, this is the second area where R&D dollars should be applied.

All other areas mentioned have sufficient R&D funds now being applied to bring forth something useful and probably significant within the next five years. Coatings and component repair do not. It is impossible to answer the question of how much more is needed since this depends entirely on a critical assessment of the problem and the method for controlling (or not controlling) dispersion of funds. Considering the two problem areas mentioned, the rate at which they have developed, and their magnitude, it seems necessary to support all levels from basic research through engineering development, including manufacturing technology.

Ceramics:

The application of ceramics to turbine nozzles and blades in man-rated engines is too far downstream to recognize a likely time period. In general there are three links in the chain of events that must be completed before we can reasonably expect this application: a) further work is needed on designing and testing hardware to b) build the confidence engine manufacturers need to change materials and c) to demonstrate the cost effectiveness of the finished product (acquisition and life cycle costs).

It is true that further research is needed on multiphase systems to understand them and that manufacturing procedures need further development to assure a uniform, reliable product. The return from increased R&D spending in these areas over the next ten years will be significant. Likely targets for the application of ceramics will not be man-rated engines but turbines for vehicles, stationary power generators, and missiles if the cost is low.

Ceramics, however, are also developing oxidation problems and this is the controlling factor with regard to the upper useful temperature limit of the material. Gas temperature limit is controlled by designers.

The proper amount of R&D funds to be spent in overcoming these deficiencies again depends on control of dispersion.

Answer to Question B:

Fabricating techniques are available to produce something useful from each of the material categories listed. Therefore, fabrication is not a pacing technology from the point of view of seeing these materials enter service. On the other hand, from the point of view of affordability, there are significant problems which need to be worked out.

Fabrication costs are high; supported in some cases by high reject rates. Repair of damaged components, mentioned earlier, should also be included in the fabrication category and some of these techniques have yet to be determined. It is important to note that as long as a customer exists who is willing to pay the price, the high cost of fabrication is not a problem. But this is a state which is not likely to continue now

that the sources of these costs are being identified. It is to be expected, therefore, that funding to support technological advances in fabrication will increase.

Answer to Question C:

As noted, design establishes the turbine inlet temperature for metal parts by providing cooling for components in the gas stream and allowing the gas temperature to rise above the material temperature. Therefore, the turbine inlet temperatures I have listed are controlled by design. I have been conservative in writing down probable upper temperature limits because of my concern for the loss of cooling.

Turbine inlet temperatures (T.I.T.) are average values. Local temperatures may vary widely around the nozzle ring so the gas temperature may be further above the material than the reported T.I.T. would indicate. This, coupled with the possibility of a local loss of cooling, forms the basis of my conservatism for metals.

Ceramics are assumed to be limited primarily by a material problem, oxidation. Since there exists no clear way out of this problem, my estimates for ceramics are conservative also.

Since I am concerned about the material temperature/T.I.T. spread today, I would not encourage further developments in this area now. It seems more important to ask for improvements in the combustor pattern factor and for developments which will assure that catastrophic failure will not occur on loss of cooling.

Answer to Question D:

Since there can be no assurance of R&D success, the answer to this question has to be "No". But if we accept that the probability of success increases with funding, then coating research should close the gap between "optimistic" and "expected" for all materials. I have expressed my concern over the continued use of superalloys in environments where the average gas temperature exceeds the incipient melting point of the alloy. Therefore, while coating research would be helpful here, it does nothing to relieve the problem of sudden loss of strength with incipient melting. For columbium alloys and ceramics, however, coating developments would be most helpful.

Further Discussion:

It is often stated that the particular section of the engine you have chosen is paced by material developements. In looking at further improvements in engine performance we then assume that any increase in the average turbine inlet temperature can be accommodated by the rest of the engine. This, in fact, is why the gas temperature today can be well above the maximum temperature that materials in the gas stream can endure.

This cannot go on indefinitely, of course, since cooling air for nozzles and first stage rotor blades must be taken from the high pressure end of the compressor; and we are therefore throwing away "work". But we have already progressed to a point where a disruption in cooling can be rather quickly fatal to the engine. In spite of this we are continuing a technology push with the same type of materials and more complex cooling schemes.

Why is this so? I think the answer is confidence. Materials for gas turbine engines are not selected by material developers, and their selection is not approved even by a designer, but by a project manager. This person's confidence in the materials approved is based largely on his earlier engineering experience. Thus, materials he is familiar with, or their derivatives, tend to remain in service. The other side of the argument is that it is easier for engineers to be confident of engineering design than material design.

This "confidence barrier", then, is what new classes of materials must overcome in order to enter service. If this is to occur by a technology push, new materials need a large and visible data base. Using superalloys as an example, we might expect to spend as much as $15,000,000 for the creation, acceptance, and bill-of-materials listing of each new alloy (metal or ceramic) for man-rated gas turbine engines after general confidence is established. Perhaps 15-20% of this will be spent on research and the rest on engineering and manufacturing developments. Considering the present state of the economy, I am not sure that a compelling incentive for spending this level of money on new materials exists.

PART 3

ADMINISTRATION QUESTIONS

1. Do you consider yourself an expert in gas turbine engines:

	Yes	No
a. Design	____	_x_
b. Materials	____ x	____
c. Development	____ x	____
d. Overall	____ x	____

2. Is your expertise limited to one particular material technology or engine component:

   No _x_

   Yes ____

   If yes, which one ________________

3. Would you like to obtain feedback from this questionnaire?

   No ____

   Yes _x_

(RESPONSE B)

do we cool or not
do we coat or not.
To go above 1st 2 lines must ~~coat~~ cool & coat!
so - I assume cooling + coating as noted.

Table 1
FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE NOZZLE DIAPHRAGM

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F Pessimistic	Expected	Optimistic
1. Superalloys	1650	1800	1900
2. Superalloys with Cooling	1650	1800	1900
3. Coated Refractories cooled	3000	3200	3400
4. Oxide Dispersions cooled coated	"	"	"
5. Directionally Solidified Superalloys cooled coated	"	"	"
6. Directionally Solidified Eutectics cooled coated	3200	3400	3600
7. Ceramic Composites " "	"	"	"
8. Ceramics "	2300	2400	2500
(Other)			

what's difference between Refractory & Superalloy?

Table 2
FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE TURBINE BLADES

	Estimated Capability Turbine Inlet Gas Temperature, °F		
Material Technologies	Pessimistic	Expected	Optimistic
1. Superalloys	1650	1800	1900
2. Superalloys with Cooling	1650	1800	1900
3. Coated Refractories + Cooling	3000	3200	3400
4. Oxide Dispersions cooled + Coated	"	"	"
5. Directionally Solidified Superalloys Cooled + Coated	"	"	"
6. Directionally Solidified Eutectics Cooled + Coated	3200	3400	3600
7. Ceramic Composites Cooled + Coated	"	"	"
8. Ceramics Coated	2300	2400	2500
(Other)			

PART 2

Making the estimates for Part 1 required implicit assumptions regarding the progress of a number of influencing factors in the material application technology. The purpose of this part of the questionnaire is to provide you an opportunity to make explicit some of these assumptions. Where appropriate, please provide any qualifying statements that would clarify the basis for your answer. See notes on Pages

QUESTION A

Oftentimes a specific material property limits its application, and if this particular property can be improved through research, the material can then be used in more advanced applications. In your estimate of turbine inlet temperatures for the various classes of materials, you assumed advances in certain physical, structural, chemical, or thermal properties. Please list the more important developments that are required for each material technology and indicate whether these efforts are supported by R&D funding at a sufficient level to bring your estimates to fruition. If not, what additional support is required? Items 6, 7 & 8 do not have adequate technological pressure applied to them and such additional effort is considered essential to success. Coatings need additional effort

QUESTION B

In some cases current fabricating techniques may be inadequate or inappropriate for new material technologies. In your opinion, would fabrication developments be required to support your material capability estimates given in Part 1? Important fabrication technologies might include hot die forging, diffusion bonding, solidification techniques, powdered metallurgy, etc. The Fabrication techniques are basically identified by the Title but some refinement is essential

QUESTION C

Describe any special design concepts which you have assumed in your temperature estimates in Part 1. Would these concepts require a development effort not currently contemplated and/or funded? No

QUESTION D

Your estimates in Part 1 were based, among other things, on the availability of likely R&D funding. Here we would like to obtain your opinion of the sensitivity of those estimates to a shift in research priorities. Can you identify any specific changes or additions to R&D fund allocations which would significantly change your estimates given in Part 1, for example, convert your "optimistic" estimate to an "expected" result.

a technique to maintain and design to a more desirable and uniform ~~[illegible]~~ radial and circumferential temperature profile entering the turbine section.

a more effective cooling scheme could also accomplish this end.

Temperatures & cooling air are a closely related pair. The values estimated are based on a reasonable limit in cooling air.

PART 3

ADMINISTRATION QUESTIONS

1. Do you consider yourself an expert in gas turbine engines:

	Yes	No
a. Design	X	
b. Materials		X
c. Development	X	
d. Overall	X	

2. Is your expertise limited to one particular material technology or engine component:

   No X

   Yes ____

   If yes, which one ____________________

3. Would you like to obtain feedback from this questionnaire?

   No ____

   Yes X

(RESPONSE C)

Table 1

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE NOZZLE DIAPHRAGM

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F Pessimistic	Expected	Optimistic
1. Superalloys	1787	1865	1942
2. Superalloys with Cooling	LOCALLY	STOICHIOMETRIC	
3. Coated Refractories	NOT AVAILABLE	IN	TIME
4. Oxide Dispersions	1853	1971	2089
5. Directionally Solidified Superalloys	1853	1934	2015
6. Directionally Solidified Eutectics	NOT AVAILABLE	IN	TIME
7. Ceramic Composites	NOT AVAILABLE	IN	TIME
8. Ceramics	NOT AVAILABLE	IN	TIME
(Other)			

Table 2

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE TURBINE BLADES

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F Pessimistic	Expected	Optimistic
1. Superalloys	2231	2256	2280
2. Superalloys with Cooling	3046	3197	3347
3. Coated Refractories	NOT AVAILABLE	IN	TIME
4. Oxide Dispersions	VERY DOUBTFUL	IN TIME	SCALE
5. Directionally Solidified Superalloys	2352	2400	2447
6. Directionally Solidified Eutectics	NOT AVAILABLE	IN	TIME
7. Ceramic Composites	NOT AVAILABLE	IN	TIME
8. Ceramics	NOT AVAILABLE	IN	TIME
(Other)			

Thank you for your letter of the 27th January 1976 and the enclosed questionnaire on the subject of possible future turbine inlet gas temperatures. You will find attached the questionnaire forms completed. This was done by a group of three appropriate specialists here.

In completing the questionnaire, we assumed that the turbine inlet gas temperature implied the average gas temperature at outlet from the combustion chamber. We also assumed that this temperature referred to the most damaging condition occurring in the flight plan. We took it that the date (1990) referred to an 'in-service' date and that therefore the design would have to be committed several years in advance of this date.

Even after making these assumptions, we found that there was a large amount of scope for the imagination in completing the questionnaire. This can be best seen with respect to answer No. 2 on table 1, where limitation due to the inlet guide vane is quoted as being 'beyond stoichiometric'. This is largely due to your statement that only the limitations due to the component itself should be considered and not other limitations in the cycle. We in fact assumed that there would be no limitation to the employment of cooling air despite the detrimental effects of large quantities of cooling air on both the thermal efficiency of the cycle and on the aerodynamic efficiency of the turbine. On the other hand, we did not employ unreasonable blade dimensions simply in order to ease the cooling problems. We also had to make some assumptions about the

type of engine, and in fact, we assumed a reasonably high compression ratio (for a Military engine) and that the worst conditions would occur at a Mach number of about 2.

Even then we had to make some assumptions about the nature of the traverse out of the combustion chamber both from the point of view of local hot spots approaching the nozzle guide vanes and the radial traverse approaching the rotor blades. We think our assumptions are reasonable but quite small changes to these numbers can make a substantial difference to the numerical values of the replies.

I should perhaps also comment on the fact that we have given our answers to four significant figures. This does not imply that our 'prophesies' are of this order of accuracy, but simply that these were the numerical values arising from our calculations and it seemed wiser not to round them off, in case we wish to refer back to the original calculations at some later date.

Although the questionnaire was completed by three of our specialists, it should not be taken as giving a considered view of the Company, nor, for that matter, my own views.

With regard to part 2, we wish to make the following comments:

QUESTION A

The non-metallic materials are limited by lack of ductility. The particular individuals, who completed the questionnaire, considered that the design difficulties brought about by this lack of ductility could not be solved reliably within the timescale stated.

QUESTION B

There are no fabrication techniques involved in the answers to Part 1, which it would be suitable to describe in this questionnaire.

QUESTION C

Although some advances in design concept are assumed in the answers to Part 1, no detailed work has been done to define these within the scope of the present exercise.

QUESTION D

We do not feel able to comment on this point.

PART 3

ADMINISTRATION QUESTIONS

1. Do you consider yourself an expert in gas turbine engines:

	Yes	No
a. Design	✓	
b. Materials	✓	
c. Development	✓	
d. Overall	✓	

Group of 3

2. Is your expertise limited to one particular material technology or engine component:

No ✓

Yes ____

If yes, which one ____________

3. Would you like to obtain feedback from this questionnaire?

No ____

Yes ✓

Table 1

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE NOZZLE DIAPHRAGM

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F		
	Pessimistic	Expected	Optimistic
1. Superalloys	1850	1900	2000
2. Superalloys with cooling	2600	2800	3600
3. Coated Refractories	1600	2400	2800
4. Oxide Dispersions	1850	2000	2050
5. Directionally Solidified Superalloys	1800	1850	1950
6. Directionally Solidified Eutectics	1750	2000	2100
7. Ceramic Composites	1700	2400	2800
8. Ceramics	1700	2400	2800
(Other)			

Table 2

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE TURBINE BLADES

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F		
	Pessimistic	Expected	Optimistic
1. Superalloys	1850	1900	2000
2. Superalloys with Cooling	2600	2800	3600
3. Coated Refractories	1600	2400	2800
4. Oxide Dispersions	1850	2000	2050
5. Directionally Solidified Superalloys	1800	1850	1950
6. Directionally Solidified Eutectics	1750	2000	2100
7. Ceramic Composites	1700	2400	2800
8. Ceramics	1700	2400	2800
(Other)			

Part 2 of your questionnaire asked for discussion of the underlying assumptions upon which the Table 1 and 2 estimates were based. As you will note, we have indicated the same values of turbine inlet temperature (equivalent to combustor exit temperature in PWA terminology) for nozzles and blades even though the relative gas temperature is lower for the blades because of a lower relative stagnation pressure. However, the blades, being a rotating component, usually experience a much higher stress condition than the nozzles, and this tends to offset the lower relative temperature of the blades for normal design lifetimes. A detailed study might reveal somewhat different values for the blades, but for a fifteen year forecast the present estimates are considered adequate.

Our answers to Questions A and B of part 2 are presented in tabular form, attached. It should be noted that our response has been framed in the context of man-rated aircraft propulsion engines. In answer to Question C, there are no special design concepts associated with the turbine inlet temperatures given in Part 1. However, in the response to Question A we have shown that "new design" concepts will probably be required to bring certain materials into use in aircraft engines.

(D)

In answering Question D, we feel that the primary effect of a shift in research priorities (hence funding levels) would be to shorten or lengthen the development time rather than increase or decrease the temperature limits.

RESPONSE TO QUESTION A, PART 2

Materials Technology	Development Required	Present R&D Support	R&D Needed
1 & 2. Superalloys	A. Alloy Development B. Process Development	Adequate	--
3. Coated Refractories	A. Better Understanding of Alloy Reactions B. Better Coatings C. Better Designs	Inadequate	>$5M
4. Oxide Dispersions	Better Processing	Inadequate	>$2M
5. D/S Superalloys	Process Control	Adequate	--
6. D/S Eutectic	A. Process Control B. Alloy Development C. Coating Development D. Better Designs	Adequate	--
7 & 8. Ceramics	A. Better Material Understanding B. Better Material C. Better Processing D. New Designs	Inadequate	>$10M

RESPONSE TO QUESTION B, PART 2

Material Technology	Fabrication Support Required
1 & 2. Superalloys	A. Powder Metallurgy
	B. Diffusion Bonding
	C. ECM/EDM
	D. Methods for Coating
	E. Hot Die Forging
3. Coated Refractories	Methods for Coating
4. Oxide Dispersions	Powder Metallurgy
5. D/S Superalloys	Sulfidation Control
6. D/S Eutectics	A. Solidification Control
	B. Methods for Coating
7 & 8. Ceramics	Powder Processing

PART 3

ADMINISTRATION QUESTIONS

1. Do you consider yourself an expert in gas turbine engines:

	Yes	No
a. Design	X	
b. Materials	X	
c. Development	X	
d. Overall	X	

2. Is your expertise limited to one particular material technology or engine component:

No __X__

Yes _____

If yes, which one ____________________

3. Would you like to obtain feedback from this questionnaire?

No _____

Yes __X__

Table 1

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE NOZZLE DIAPHRAGM

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F		
	Pessimistic	Expected	Optimistic
1. Superalloys	1850	1900	1950
2. Superalloys with Cooling	2600	3500	4000
3. Coated Refractories			
4. Oxide Dispersions	1900	1950	2000
5. Directionally Solidified Superalloys	1900	2000	2100
6. Directionally Solidified Eutectics	2050	2150	2250
7. Ceramic Composites	1900	2000	2200
8. Ceramics	2500	2600	3000
(Other)			

1. Items 4-8 assumed uncooled vane.
2. DS superalloys will probably not be needed as a vane material.
3. Items 4-7 dependent on coating technology.

Table 2

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE TURBINE BLADES

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F Pessimistic	Expected	Optimistic
1. Superalloys	1850	1850	1900
2. Superalloys with Cooling	2550	2800	3500
3. Coated Refractories			
4. Oxide Dispersions	1900	1950	2000
5. Directionally Solidified Superalloys	1950	2000	2100
6. Directionally Solidified Eutectics	1950	2100	2200
7. Ceramic Composites	2200	2400	2600
8. Ceramics	2400	2500	2900
(Other)			

1. Items 4-8 assumed uncooled blade.
2. Items 4-7 dependent on coating technology.
3. Item 3 depends upon the coating technology and may vary from 1900°F to 3000°F.

PART 2

QUESTION A

For items 4-7, it was assumed that coatings or corrosion resistance would be developed for the particular material to operate at these temperatures for extended periods.

QUESTION B

The estimates provided in Tables 1 and 2 were based on current fabrication techniques.

QUESTION C

It was assumed that design capability for ceramic material components exist.

QUESTION D

This question should be addressed by the materials developer.

PART 3

ADMINISTRATION QUESTIONS

1. Do you consider yourself an expert in gas turbine engines:

	Yes	No
a. Design	X	
b. Materials		X
c. Development	X	
d. Overall		

2. Is your expertise limited to one particular material technology or engine component:

   No _____

   Yes X

   If yes, which one TURBINES

3. Would you like to obtain feedback from this questionnaire?

   No _____

   Yes X

Table 1
Fifteen Year (1990)
Turbine Inlet Temperature Prospects
(Man-Rated Military Aircraft)

APPLICATION: FIRST STAGE NOZZLE DIAPHRAGM

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F Pessimistic	Expected	Optimistic
1. Superalloys	1900°F	2000°F	2050°F
2. Superalloys with Cooling	3000°F	3200°F	3400°F
3. Coated Refractories *	-----	-----	-----
4. Oxide Dispersions**	3000°F	3200°F	3400°F
5. Directionally Solidified Superalloys*	3000°F	3200°F	3400°F
6. Directionally Solidified Eutectics*	3000°F	3200°F	3400°F
7. Ceramic Composites***	Not Achieved	2600°F	2900°F
8. Ceramics**	Not Achieved	2900°F	3400°F
Other Ceramic-Metal Hybrid	2600°F	2900°F	3400°F

* prior extensive experience with refractory metals in gas turbines and liquid metal turbines has indicated that coated refractory metal alloys do not have the reliability required for man-rated military aircraft.

** With cooling - the amount of cooling air is reduced by using advanced materials in the following sequence:

Superalloys > Directionally solidified superalloys > Oxide dispersions > Directionally solidified eutectics

*** No cooling

Table 2

Fifteen Year (1990)
Turbine Inlet Temperature Prospects
(Man-Rated Military Aircraft)

APPLICATION: FIRST STAGE TURBINE BLADES

Materials	Estimated Capability Turbine Inlet Gas Temperature, °F		
	Pessimistic	Expected	Optimistic
1. Superalloys	1800°F	1850°F	1900°F
2. Superalloys with Cooling	3000°F	3200°F	3400°F
3. Coated Refractories *			
4. Oxide Dispersions	Not Applicable	due to inadequate strength	
5. Directionally Solidified Superalloys **	3000°F	3200°F	3400°F
6. Directionally Solidified Eutectics **	3000°F	3200°F	3400°F
7. Ceramic Composites	Not Applicable	*** →	
8. Ceramics	Not Applicable	*** →	
(Other)			

* prior extensive experience with refractory metals in gas turbines and liquid metal turbines has indicated that coated refractory metal alloys do not have the reliability required for man-rated military aircraft.

** With cooling

*** For reliability considerations

QUESTION A -- Needed Developments

Directionally Solidified Eutectics

- Alloy development
- Coating development (external & internal)
- Mechanical property characterization
- Q.C. methods, acceptability limits
- Component testing

Additional support needed $10,000,000

Ceramic Composites

- Develop impact-resistant coatings
- Develop and characterize standard grades of Si/Sic
- Inspection and Q.C. methods development

Additional support needed (see answer to Question D)

Ceramics

- Impact-resistant coatings
- Property characterization of best quality standard SiC.
- Inspection and Q. C. methods development

Additional support needed (see answer to Question D)

Oxide Dispersions

- Improved transverse strength
- Improved quality control
- Lower cost materials

Additional support needed $2,000,000

QUESTION B -- Fabrication Technologies Needed

Directionally Solidified Eutectics

- Improved ceramic mold materials
- Improved ceramic core materials
- More cost-effective solidification process
- Development of pilot line manufacturing capability for casting and coating blades and vanes
- Develop brazing technology for attaching sealing plugs, tip caps, etc.

Ceramic Composites

- Develop fabrication technology including casting and machining
- Develop pilot line manufacturing capability for nozzle vanes and band segments.
- Develop joining technology for Si/SiC to Si/SiC parts
- Develop methods of selectively "tailoring" mechanical properties in different areas of parts.

Ceramics

- Develop sintering process to produce pressureless sintered SiC with highly reproducible properties
- Develop pilot line manufacturing capability to make nozzle vanes and band segments.

QUESTION C

Air cooling design technology was assumed for cooled superalloys, oxide dispersion strengthened alloys, directionally solidified superalloys and directionally solidified eutectics, since design and material technologies are really inseparable for high performance turbines. The temperatures for the four classes of materials are thus the same. The real payoff to the engine by using the more advanced materials is in the reduction of cooling air required when the material has a higher temperature capability.

The air-cooling design technology to attain the turbine inlet temperatures indicated in Tables I and II exists today. The continued refinement of this technology will be funded by the military and IR&D program. Funding for the mechanical design technology needed for anisotropic directionally solidified eutectics, the ceramic composites, and pressureless sintered SiC needs to be identified, since the mechanical and physical characteristics of these materials will be significantly different than materials now used in aircraft turbine engines and different techniques of stress analysis and mechanical design will be required.

QUESTION D

To assure that adequate technology on directionally solidified eutectics, ceramic composites, ceramics, and ceramic-metal hybrids is available for 1990 engine applications, R&D efforts on these technologies should be accelerated in the 1979-1989 decade.

Even though efforts are underway today in American industry on all these technologies, a considerable acceleration is vital if the technologies are to be available for reliable, cost-effective use in 1990 man-rated military aircraft.

An adequate program to develop the foregoing material systems would cost $60,000,000 and require 15 years.

Table 1

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE NOZZLE DIAPHRAGM

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F Pessimistic	Expected	Optimistic
1. Superalloys	1950	2000	2050
2. Superalloys with Cooling	2700	2900	3200
3. Coated Refractories	--	--	--
4. Oxide Dispersions	2100	2200	2300
5. Directionally Solidified Superalloys	2000	2050	2100
6. Directionally Solidified Eutectics	2050	2100	2150
7. Ceramic Composites	--	--	--
8. Ceramics	2300	2500	2700
(Other) Cooled Ceramics	3000	3200	3500
Single Grain Castings	2175	2225	2275

Table 2

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE TURBINE BLADES

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F Pessimistic	Expected	Optimistic
1. Superalloys	1850	1900	2000
2. Superalloys with Cooling	2600	2800	3100
3. Coated Refractories	--	--	--
4. Oxide Dispersions	--	--	--
5. Directionally Solidified Superalloys	1900	1950	2050
6. Directionally Solidified Eutectics	2000	2100	2200
7. Ceramic Composites	--	--	--
8. Ceramics	2200	2500	2600
(Other) Cooled Ceramics	3000	3200	3500
Single Grain Castings	1950	2050	2150
ODS + γ'	2000	2100	2200
W Wire Reinforced Superalloy	2000	2150	2300

TABLE 3

	Material	Limiting Material Property (Question A)	Fabrication Techniques Req'd (Question B)	Design Concepts Req'd (Question C)
1	Superalloys	Oxidation/corrosion resistance Incipient melting temperature	Superior coating systems	
2	Superalloys & Cooled Superalloys	Thin wall properties of castings Conductivity	Casting technology	Designs incorporating full-film or transpiration cooling required for full potential
3	Coated Refractories [1]	----	----	----
4	Oxide Dispersions	Microstructure Ductility Incipient melting temp.	Powder processing-reduce cost. Joining techniques. Thermal/mechanical treatment	Designs to minimize joining complexity.
5	D.S. Superalloys	Microstructure Oxidation/corrosion resis.	Superior coatings Processing cost reduction.	----
6	D.S. Eutectics	Microstructure Transverse properties Oxidation/corrosion resis. Mold material	Superior coatings Processing cost reduction.	----
7	Ceramic Composites [1]	----	----	----
8	Ceramics [2]	Microstructure Impurity control Fracture toughness Impact resistance	Hot press to net shape Slip casting technology Joining techniques	Methods to join ceramics to metal systems. Design for brittle mat'ls
9	Cooled Ceramics [2]	Thin wall properties Fracture toughness Impact resistance	Processing hollow structures	(Same as above)
10	Single Grain Cast Superalloys [2]	Oxidation/corrosion resis. Macrostructure orientation	Casting technology Superior coatings	----

TABLE 3 (Continued)

11	ODS + γ' (2)	Microstructure Ductility Incipient melting	Powder processing Thermal/mechanical treatment	----
12	Refractory Wire (1) Reinforced Superalloy	Matrix/wire reaction Matrix/wire expansion Strength-to-density	Matrix/wire processing Lay-up bonding	Design for minimum wire loading to reduce weight.

(1) High risk - use not probable in 15 years.

(2) Additional funding would increase probability of application in 15 years (Question D).

PART 3

ADMINISTRATION QUESTIONS

1. Do you consider yourself an expert in gas turbine engines:

	Yes	No
a. Design	____	____
b. Materials	x	____
c. Development	x	____
d. Overall	____	____

2. Is your expertise limited to one particular material technology or engine component:

   No x

   Yes ____

   If yes, which one ____________________

3. Would you like to obtain feedback from this questionnaire?

   No ____

   Yes x

without size, Duty cycle, + Life requirements these Temperatures aren't very meaningful

Table 1

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE NOZZLE DIAPHRAGM

	Estimated Capability Turbine Inlet Gas Temperature, °F		
Material Technologies	Pessimistic	Expected	Optimistic
1. Superalloys	2000	2100	2200
2. Superalloys with Cooling	2800	3000	3200
3. Coated Refractories	2300	2400	2500
4. Oxide Dispersions	2200	2300	2400
5. Directionally Solidified Superalloys	2050	2150	2250
6. Directionally Solidified Eutectics	2150	2200	2250
7. Ceramic Composites ? ceramic/fiber? ceramic/metal?	2500	2700	3000
8. Ceramics	2500	2800	3000
(Other)			

Composite is lower than monolithic material due to possible interactions + reactions at hi-Temp

Table 2

FIFTEEN YEAR (1990)
TURBINE INLET TEMPERATURE PROSPECTS
(MAN-RATED MILITARY AIRCRAFT)

APPLICATION: FIRST STAGE TURBINE BLADES

Material Technologies	Estimated Capability Turbine Inlet Gas Temperature, °F Pessimistic	Expected	Optimistic
1. Superalloys			
2. Superalloys with Cooling			
3. Coated Refractories			
4. Oxide Dispersions			
5. Directionally Solidified Superalloys			
6. Directionally Solidified Eutectics			
7. Ceramic Composites	2500	2700	3000
8. Ceramics	2500	2800	3000
(Other)			

I don't know enough about creep properties of the metals to answer 1-6

PART 2

Making the estimates for Part 1 required implicit assumptions regarding the progress of a number of influencing factors in the material application technology. The purpose of this part of the questionnaire is to provide you an opportunity to make explicit some of these assumptions. Where appropriate, please provide any qualifying statements that would clarify the basis for your answer.

QUESTION A

Oftentimes a specific material property limits its application, and if this particular property can be improved through research, the material can then be used in more advanced applications. In your estimate of turbine inlet temperatures for the various classes of materials, you assumed advances in certain physical, structural, chemical, or thermal properties. Please list the more important developments that are required for each material technology and indicate whether these efforts are supported by R&D funding at a sufficient level to bring your estimates to fruition. If not, what additional support is required? (over) A

QUESTION B

In some cases current fabricating techniques may be inadequate or inappropriate for new material technologies. In your opinion, would fabrication developments be required to support your material capability estimates given in Part 1? Important fabrication technologies might include hot die forging, diffusion bonding, solidification techniques, powdered metallurgy, etc.

QUESTION C

Describe any special design concepts which you have assumed in your temperature estimates in Part 1. Would these concepts require a development effort not currently contemplated and/or funded?

A

Ceramics only

I'm assuming that sufficient progress is made in
a) ceramic - metal attachment (design + demo)
b) ceramic materials consistencies (Weibull "m" >10 in parts)
c) development of viable proof test technology

Insufficient work is currently funded
about $250K per year in a + c is needed
$1,000K " " " b " "

B Ceramics only

Development of fabrication technology must be concurrent with mat'ls Dev.

In particular we need sintered Si_3N_4 + Sintered SiC with high "m" + Improved K_{IC} (if possible)

- R&D in "Green" Body Fabrication is essential to be able to sinter parts with min. machining required.

C Ceramics only

None not now under investigation in various "ARPA" Programs

Ford
West
P&W
Garrett

QUESTION D

Your estimates in Part 1 were based, among other things, on the availability of likely R&D funding. Here we would like to obtain your opinion of the sensitivity of those estimates to a shift in research priorities. Can you identify any specific changes or additions to R&D fund allocations which would significantly change your estimates given in Part 1, for example, convert your "optimistic" estimate to an "expected" result.

In the materials area itself none
In the exploitation (i.e. demonstration in systems) area the more $ the faster

PART 3

ADMINISTRATION QUESTIONS

1. Do you consider yourself an expert in gas turbine engines:

	Yes	No	
a. Design	X		for a materials person
b. Materials	X		
c. Development	X		
d. Overall	X		

2. Is your expertise limited to one particular material technology or engine component:

   No ____

   Yes X — one field of materials

   If yes, which one Ceramics

3. Would you like to obtain feedback from this questionnaire?

   No ____

   Yes X

Appendix D

MATERIAL SUPPLY/DEMAND DATA SHEETS

This appendix contains the availability data sheets compiled for ten basic materials.* These materials represent selected constituents of the high temperature materials under study. Their selection is based on the possibility that they may be in short supply in 1990.

In an economic sense, the price coupling of supply and demand insures that they will be in balance. The data accumulated here pertain to factors that could cause supply or demand perturbations in the 1990 time frame from an otherwise smooth time-transition of U.S. supply and demand production functions.

The data sheets contain information pertinent to these issues:

1. The continuity of worldwide production capacity and distributional patterns.
2. The potential for supply interruption to the United States.
3. The possible causes of U.S. economy-wide demand variations.

The materials treated are:

Chromium, Cr	Tungsten, W
Cobalt, Co	Hafnium, Hf
Nickel, Ni	Tantalum, Ta
Columbium (Niobium), Cb	Thorium, Th
Titanium - Rutile Ore - Metal, Ti	Zirconium, Zr

---

*Reference sources are listed at the end of the appendix.

METAL: TITANIUM-RUTILE ORE (1,000 ST) RISK CATEGORY DATA SOURCE

1) Supply/World Production Capacity and International Distribution Pattern

Reserves:	World	U.S.	"Friendly"	3rd World	Unfriendly	Data Source
	13,000	500	8,000 (Australia, 90% of world's rutile)	3,900	300	[1]

Mine Production:	World	World Growth Rate	U.S.	U.S. % of World	Data Source
	1974^e: 353	Decreased 7% ('73-'74)	6	2%	[1]

U.S. Refining:

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000: [6]

U.S.	Rest of World	World
1.8	--	--

U.S. Production/U.S. Demand, Primary Mineral (%):	1950	1960	1970	1974	2000	Data Source
	--	--	--	2%	--	[1]

Consumption:	U.S.	U.S. % of World Production	U.S. % of World Production (Past)	Data Source
	1974^e: 280	1974: 79%	1973: 74%	[1]

Technological Advances: Synthetic rutile from illmenite (imported from Japan, Australia and India[1]: 34,000T in '74) This would make available large US illmenite reserves (~100 MST) for Ti production. [13]

Capital Investment Problems: Insufficient economic incentive to encourage private investment into synthetic rutile production because of large reserve to production ratio and friendly relations with Australia. [7]

Environmental Constraints: Australia is impeded from mining more of its rutile sands because of environmental pressure. [1] Synthetic approach using direct chlorination present some environmental problems for the US. [13] It is environmentally cleaner to make pigment from rutile than from illmenite. [1]

2) Supply/Interruption

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Australia	91	28	26	19
India	5	-	-	-
Sierra Leone	4	-	-	-

Cartel Prospects
Embargo
Secondary Conflicts

Given Australia's strong political and economic ties to the West, interruption is unlikely but a price increase is possible. [12]

3) Demand

New Uses:

Substitutions, Functional and Material: Illmenite could be substituted for rutile thereby preserving rutile for metal production; this might cause some environmental problems for US due to chlorine process involved in making pigment from illmenite. [1]

End Use, %: Titanium oxide pigment, 86% [1]
Welding-rod coatings, 78%
Miscellaneous, including metal and glass fibers, <1%, alloys, carbide and ceramics

U.S. Consumption Derived from Recycling:

U.S. Primary Mineral Demand, Average Annual Growth, %: [5]

1950-1960	1960-1970	1950-1973	1973-2000
-	-	-	-

DOD Consumption as % of National Consumption:

NOTE: Entries in the table that are estimates are identified with the superscript letter "e".

METAL: TITANIUM (1,000 ST metal) RISK CATEGORY DATA SOURCE

1) Supply/World Production Capacity and International Distribution Pattern

Reserves: World U.S. "Friendly" 3rd World "Unfriendly"
See Rutile sheet.

Refinery Production: World	World Growth Rate	U.S.	U.S. % of World	
Sponge Capacity[e]: 56. Declining; plants are closing.		18.	32%	[1]

U.S. Refining: Excess capacity. [7]

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000: [6]

U.S.	Rest of World	World
1.1	4.2	3.3

U.S. Production/U.S. Demand, Primary Mineral (%): 1950 1960 1970 1973 2000
60% (sponge capacity) [1 & 2]

Consumption: U.S. 1973: 30 [2] U.S. % of World Production 54% [1 & 2] U.S. % of World Production (Past) -

Technological Advances: *Foreign sponge is produced in newer plants that use the vacuum-distilled process* which produces a purer product. Future trends in Ti production will depend on the economics of energy costs of direct chlorination, as opposed to the costs of upgrading illmenite to 95%-plus TiO_2 and subsequent conversion to $TiCl_4$. [13 & 16]

Capital Investment Problems: No problem. World and US have excess plant capacity to produce sponge. US investment in modernizing plants is depressed only about 3% because of cheap imports. [4 & 7]

Environmental Constraints: Disposal problem of mud and slimes from dredging and concentrating Ti from sand deposits would accompany expanded US production. Commercial development of rutile substitutes from illmenite might result in generation of large quantities of solid waste containing iron. [4]

2) *Supply/Interruption*

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Metal: Japan	68	<1	350	1
USSR	24	-	-	-
U.K.	8	-	-	-
Ore: Australia (rutile)	-	28	26	19
Canada (illmenite)	-	24	47	22
Norway	-	3	10	<1
France	-	0	-	1/47%

Cartel Prospects
Embargo
Secondary Conflicts

US could produce its entire demand in case of sponge embargo. It would require increasing rutile imports. Appropriate allocation of sponge would probably serve DOD needs. [12]

3) Demand

New Uses: Industrial and commercial: bicycles, golf clubs, heat exchanger tubes.

DOD share (about 42%) has decreased sharply because of substitutions. [16]

	'61	'71	'73
DOD aircraft	63	30	34
Commercial Aircraft	14	46	41
Missiles/Space	16	7	7
Helicopter Ord.	2	1	1
Industrial	5	16	17

Substitutions, Functional and Material: Composite materials for low and medium temperature applications. Superalloys for high temperature applications. A number of materials, e.g., Zn oxide, talc, clay, silica, alumina substitute for TiO_2 as paint pigment. Illmenite, Ti slag and manufactured TiO_2 can be substituted for rutile in welding rod coatings. [4]

End Use, %: 87% in jet engines, airframes, and space and missile applications;
3% in chemical processing industry and in marine and ordnance applications. [1]

U.S. Consumption Derived from Recycling: 31%. [4 & 7]
Problem of increasing is that the purity of the Ti decrease to the point where DOD use is excluded.

U.S. Primary Mineral Demand, Average Annual Growth, %: [5]

1950-1960	1960-1970	1950-1973	1973-2000
23.0	11.6	13.9	2.3

DOD Consumption as % of National Consumption: 4% [15]

METAL: NICKEL (1,000 ST metal) **RISK CATEGORY** **DATA SOURCE**

1) Supply/World Production Capacity and International Distribution Pattern

Reserves:	World	U.S.	"Friendly"	3rd World	"Unfriendly"	
	49,000	200	8,000	21,200	10,000	[1]

Mine Production:	World	World Growth Rate	U.S.	U.S. % of World	
	1974^e: 757	4.8%/yr ('64-'73)	17.	2%	[1]

U.S. Refining: Expansion of the one domestic processor (Louisiana): will produce 40,000 ST/yr, estimate. Also copper mining byproduct. [1]

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000:

U.S.	Rest of World	World	
-	2.2	1.6	[6]

U.S. Production/U.S. Demand, Primary Mineral (%):	1950	1960	1970	2000	
	1.0	10.3	9.8	8.6	[5]

Consumption: U.S.	U.S. % of World Production	U.S. % of World Production (Past)	
1974^e: 210	1974^e: 28%	1964: 32% [2]	[1]

Technological Advances: Manganese nodule mining may lower Mn and Co prices (Ni substitutes). Also contains Ni. New extraction from lateritic ores has opened new operations in developing countries. Inco (mostly), Bureau of Mines, Netherland, and universities have developed new mining techniques. [7 & 13]

Capital Investment Problems: Many newly announced mining projects (e.g., Inco in Canada, Indonesia, Guatemala). However, capital costs continue to rise because of increased expenditures on supplies, services, labor, energy.[13] Price will continue to rise over next decade because mining, processing, refining of newer deposits is more complex than for old sulfide deposits.[7] If Ni prices doubled, US import dependence would probably fall from current 65% to 20-30%.[12]

Environmental Constraints: Environmental impact increases as world's supply base shifts to open pit laterite mining (heavy rainfall causes erosion problems). The one US Ni smelter has 98% control of stack emissions (no air pollution problems). [1]

2) Supply/Interruption

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Canada	76	37	56	58
Norway	8	-	-	-
USSR	-	20	<1	<1
N. Caledonia	-	16	10	4
Dominican Republic	-	3	13	1
Rhodesia	-	2	14	<1
South Africa	-	2	23	1
Greece	-	2	7	<1
U.K.	-	0	-	3
Other	16	1	28	1/70%

Cartel Prospects
Embargo
Secondary Conflicts

Prices have already reached cartel maximizing levels; therefore, a formal cartel would not revise current pricing strategy much. Alternate supply potential in Guatemala and Colombia. *New operations in developing nations: could unite.[7] [12]

3) **Demand**

New Uses: In desalinization plants.
More nickel-containing alloys. [13]

Substitutions, Functional and Material: No completely satisfactory substitution in any of its uses.[7] But at appropriate prices various mixes of Cr, Mn, Mo and Co could partially substitute. However, for critical high-performance turbojet engines and gas turbines there is no substitute for Ni-base superalloys. Greatest opportunities for substitution: corrosion resistance, high strength, or electronic and magnetic properties, e.g., Ti-clad carbon steel, some plastics, cobalt, etc. Newly developed techniques to make stainless steel without Ni may erode Ni markets.[12] Limited supply and high costs are forcing much research on substitutions.[4]

End Use, %: Transportation, 21; Chemicals, 15; Electrical Equipment, 13; Fabricated Metal Products, 10. Stainless steels account for 33% of total Ni consumption.[7] [1]

U.S. Consumption Derived from Recycling: 35% (1972). Good increasability. [9]
About 12.5% of annual US supply is from secondary recovery; considerable room for improvement. [7]

U.S. Primary Mineral Demand, Average Annual Growth, %:

1950-1960	1960-1970	1950-1973	1973-2000	
2.0	2.5	2.9	2.6	[5]

DOD Consumption as % of National Consumption: 7% [15]

METAL: CHROMIUM (1,000 ST metal) RISK CATEGORY DATA SOURCE

1) Supply/World Production Capacity and International Distribution Pattern

Reserves:	World	U.S.	"Friendly"	3rd World		Unfriendly	
	132.	0	0	131.379 / 123.400	South Africa: 63% / Rhodesia: 33%	.621 / 8.6	[1] [3]

Mine Production:	World	World Growth Rate	U.S.	U.S. % of World	
	2.386 (USSR & S. Africa ≈1/2 production)	4%/year ('64-'73)	0 (ceased '61)	0	[2]

U.S. Refining:
Decreasing trend because of a) foreign ferrochromium increasing (20% from '68-'72); ore imports decreasing; b) increased labor rates; c) environmental regulations. [11]

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000:

U.S.	Rest of World	World	
-	6.4	5.1	[6]

U.S. Production/U.S. Demand, Primary Mineral (%):	1950	1960	1970	2000	
	-	7.9	-	-	[5]

Consumption:	U.S.	U.S. % of World Production	U.S. % of World Production (Past)	
	1973: .543	1973: 23%	1964: 37%	[2]

Technological Advances: Processes have been developed to use South African chemical grade ore in metallurgical applications. Effect--reduces US dependence on USSR and Rhodesian metallurgical grade ore. Research on stainless steel production directly from chromite without first converting to ferro-chromium. Bureau of Mines research to recover Cr from secondary sources. [4] [7] [4]

Capital Investment Problems:

Environmental Constraints: Processing plants generate dust emissions that are controlled to meet EPA standards. However, disposal of reclaimed dust and slag (generated during smelting) remains a problem. Refractory and chemical use of ore cause burnt-out refractories and iron-sludge disposal problems. [7]

2) *Supply/Interruption*

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Chromite:				
USSR	31	33	19	25
South Africa	29	23	20	18
Turkey	18	10	17	6
Philippines	15	4	32	5
Iran	-	3	6	<1
Pakistan	-	<1	73	1
Other	7	-	-	8
Ferrochromium:				
South Africa	36	-	-	-
South Rhodesia	16	6	28	7
Japan	13	-	-	-
Other	35	-	-	-/70%

Cartel Prospects / Embargo / Secondary Conflicts: US embargo to Rhodesia '67-'71 increased dependence on USSR (raised prices). Supply restrictions by a South African-Rhodesian cartel would require only tacit cooperation by USSR as is occurring in diamonds. However, the major metallurgical ore producers (USSR, Rhodesia, South Africa, Turkey) are an unlikely combination for joint action because a) structure of industry, b) differing political/economic orientation. [12]

3) Demand

New Uses: "Cr-plated steel" for container use [4]

Substitutions, Functional and Material: Material: Stainless Steel: No overall substitution for chemical process equipment or high temperature applications requiring corrosion or oxidation resistance. In small quantities (5% of total stainless capacity) copper-nickel or titanium-base alloys could be substituted at higher cost. [10] Alloy Steel: Substitutions usually feasible. Refractories: Magnesite in some applications. Chemicals: Substitutions in major uses feasible. Foundry: Substitute zircon sand. Functional: Can substitute Al or Ti or nonferrous metal, e.g., Ni, instead of stainless steel except in certain applications, e.g., those requiring sterilization.

End Use, %: Construction, 23; Transportation, 18; Machinery and equipment, 15; Refractories, 13; Others, 31. [61% of total Cr usage for ferrochromium in stainless & alloy steels (requires metallurgical grade ore)] [1]

U.S. Consumption Derived from Recycling: 15% (1972) mostly from stainless steel scrap. [9]
extent to which significant amounts of Cr could be recovered from obsolete scrap is unknown. [7]

U.S. Primary Mineral Demand, Average Annual Growth, %:

1950-1960	1960-1970	1950-1973	1973-2000	
4.5	2.7	3.8	2.6	[5]

DOD Consumption as % of National Consumption: 6% [15]

METAL: COLUMBIUM (1,000 ST metal) — RISK CATEGORY — DATA SOURCE

1) Supply/World Production Capacity and International Distribution Pattern

Reserves: World 6,400; U.S. 0; "Friendly" 750 (Canada); 3rd World 4,901 (Brazil:2/3 world reserves); Unfriendly 750^e (USSR); NA (Other Communist countries) [3]

Mine Production: World 11.665 (Brazil,>1/2); World Growth Rate 9%/yr ('64-'73); U.S. 0; U.S. % of World 0 [2]

U.S. Refining: Metals and alloys are produced from imported concentrates, tin slags, and ferrocolumbium. [1]

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000: [6]

U.S.	Rest of World	World
0	10 or more	9.4

U.S. Production/U.S. Demand, Primary Mineral (%): [5]

1950	1960	1970	2000
-	-	-	-

Consumption: U.S. 1974^e:1.0; U.S. % of World Production 1973: 8.6%; U.S. % of World Production (Past) 1970: 17% - 25% [1 & 2] [1]

Technological Advances: Worldwide research developments have recently and successfully been applied to the commercial exploitation of pyrochlore deposits in Brazil, Canada, and the Congo. [4]

Capital Investment Problems:

Environmental Constraints: No problem. [4]

2) Supply/Interruption

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Brazil	91	53	26	48
Malaysia	2	<1	13	<1
Zaire	2	<1	18	<1
Canada	-	20	<1	<1
Nigeria	-	10	33	12
Thailand	-	5	45	8
U.K.	-	0	-	1
Other	5	<1	83	3/74%

Cartel Prospects / Embargo / Secondary Conflicts: Highly unlikely, given the array of other substitutable materials. [12]

3) Demand

New Uses: Several developments in the use of Ni HSLA steels in the automotive industry as well as in pipelines, machinery parts and construction steels indicate increased applications (increased demand). Very large growth in demand when superconductors are utilized. Decline in demand as a carbon stabilizer in stainless steel. [13]

Substitutions, Functional and Material: Vanadium can be substituted for or interchanged with Cb as an alloying agent in high strength steels. Tantalum can be substituted in stainless and high-strength steels. High Temperature applications--substitute molybdenum, vanadium, tungsten, tantalum, ceramics, glass-reinforced plastics, etc. Corrosion-resistant equipment--substitute tantalum, titanium, platinum, and glass.[4] Industry wants to substitute Nb (because it is more abundant through imports and less expensive) for other alloying elements in steel.[7]

End Use, %: Construction, 40; Oil and Gas Industries, 18; Machinery, 20; Transportation, 20; Other, 2.

U.S. Consumption Derived from Recycling: None is recovered. Very low chance of increasing secondary source recovery. Scrap accounted for less than 1% consumption.[3] [7]

U.S. Primary Mineral Demand, Average Annual Growth, %: [5]

1950-1960	1960-1970	1950-1973	1973-2000
37.0	7.5	19.5	5.0

DOD Consumption as % of National Consumption: 6% [15]

NOTE: Columbite-Tantalite ore is mostly a coproduct of tin mining.

METAL: ZIRCONIUM (1,000 ST metal) RISK CATEGORY — DATA SOURCE

1) Supply/World Production Capacity and International Distribution Pattern

Reserves: World	U.S.	"Friendly"	3rd World	"Unfriendly"	Data Source
27,000	6,000	14,350	3,650	3,000	[3]

Mine Production: World	World Growth Rate	U.S.	U.S. % of World	U.S. Prod. Growth	Data Source
1973: 314.175	4%/yr ('68-'73)	60% (increased 10% in '74)	19.1%	7%/yr ('68-'73)	[2 & 4]

U.S. Refining: Yes

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000:

U.S.	Rest of World	World	Data Source
1.5	2.0	1.8	[6]

U.S. Production/U.S. Demand, Primary Mineral (%):	1950	1960	1970	1972	2000	Data Source
				70.6		[2 & 3]

Increase in demand will probably be met by increased domestic production.[1]

Consumption: U.S.	U.S. % of World Production	U.S. % of World Production (Past)	Data Source
1972^{e}: 85.0	1972: 27%	1968: 21% [4]	[3]

Technological Advances: Bureau of Mines is studying means for recovery of marketable grade Zr concentrate from Florida phosphate and other nonmetallic mining and processing operations. [4]

Capital Investment Problems: A rise in Zr price and technological advances could make it economically feasible to recover Zr as a byproduct of nonmetallic mining operations. [4]

Environmental Constraints: The mud and slime associated with zircon recovery from sand deposits constitute a disposal problem, e.g., when environmental considerations restrict production of Ti from sand, so that Ti rock ore will be used instead. Tailing disposal, land reclamation, water pollution control. [4]

2) Supply/Interruption

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Australia (world's largest producer)	94	NA	NA	NA
Canada and South Africa	6	NA	NA	NA

Total Imports as % of U.S. Consumption:	1950	1960	1971	1972^{e}	Data Source
	25%	35%	58%	41%	[3]

Cartel Prospects
Embargo
Secondary Conflicts
} Not likely.

3) Demand

New Uses: The major growth areas for the mineral zircon are in refractories, abrasives, and chemicals, and for zirconium metals are in material for constructing nuclear reactors, in refractory alloys, and in chemical processing plants.[1] Zr may also find increased application in superconducting magnets and in fuel cells.[4]

Substitutions, Functional and Material: Foundries: substitute olivine, chromite sand, quartz sand or other sand in place of zircon. Zirconia: substitute other refractories and ceramics. Zirconium: substitute other corrosion resistant metals with possible exception in nuclear equipment (2%). [3]

End Use, %: Foundry sands, 53; Refractories, 15; Ceramics, 13; Zr metal used in alloys for nuclear and refractory applications and in chemical processing equipment, 19. [illegible]

U.S. Consumption Derived from Recycling: Less than 1% of annual metal supply is reclaimed.[3] Up to 75% Zr may be recoverable in foundry applications; 1968, 2,500 T Zr recovered.[4]

U.S. Primary Mineral Demand, Average Annual Growth, %:

1950-1960	1960-1970	1950-1973	1973-2000
17.5	-	3.1	6.0

DOD Consumption as % of National Consumption: 6.5%, 1972.

NOTE: Zr is a byproduct of Ti. The forecast rate of increase of demand for and production of Ti exceeds that for Zr; therefore, it seems likely that Zr will be in excess supply at least during the next [illegible] years.

METAL: THORIUM (1,000 ST) RISK CATEGORY DATA SOURCE

1) Supply/World Production Capacity and International Distribution Pattern

Reserves: ThO_2	World	U.S.	"Friendly"	3rd World	"Unfriendly"	
	400	110	120	170	20	[1]

Mine Production:	World	World Growth Rate	U.S.	U.S. % of World	
	1974^e: 1.040	4.9%/yr ('64-'73)	0.1	10%	[1]

U.S. Refining: Nine companies processed or fabricated Th in 1974. [1]

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000:

U.S.	Rest of World	World	
10 or more	10 or more	10 or more	[6]

U.S. Production/U.S. Demand, Primary Mineral (%):	1950	1960	1970	2000	
	143.5	-	74.1	7.7	[5]

Consumption: U.S.	U.S. % of World Production	U.S. % of World Production (Past)	
1973: 0.09	1973: 8.9%	1964: 5.26%	[2]

Technological Advances:
Improved mining and processing technology. [4]

Capital Investment Problems: High Temperature Gas-Cooled Reactor (HTGR) uncertainties make investment questionable. Cheapest to import monazite. Growth in historical demand for Th has been inadequate to develop an independent Th industry. [4]

Environmental Constraints: Conflict with urban and recreational facilities from mining monazite placers along beaches and rivers. Radiation toxicity.[4] [1]

2) Supply/Interruption

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Australia	35	29	1	3
Malaysia	58	12	47	41
Other	7	-	-	-/44%

Cartel Prospects
Embargo
Secondary Conflicts
Very low probability. [4]

3) Demand

New Uses: New applications as a high temperature superconductor alloying element.[4] Based on projected HTGR development, demand for Th is expected to increase at an average annual rate of 10-12% through 1985.[1] No indication that non-nuclear applications will lead to a significantly higher demand.[13]

Substitutions, Functional and Material: No satisfactory substitutions for most nonenergy uses, especially in gas mantles and in alloys. Zr and Ti are superior in electronic tubes. Beryllia and Yttria can be substituted as a refractory above 2,000°C. U^{238} substituted for fuel. [4]

End Use, %: Nuclear Reactors, 50; Lamps and Lighting, 20; Aerospace, 5; Refractories, 5; Other, 10. [1]

U.S. Consumption Derived from Recycling: Insignificant. [3]

U.S. Primary Mineral Demand, Average Annual Growth, %:

1950-1960	1960-1970	1950-1973	1973-2000	
16.9	0.2	6.1	9.7	[5]

DOD Consumption as % of National Consumption: 11% [15]

METAL: TUNGSTEN (1,000 ST metal) RISK CATEGORY DATA SOURCE

1) Supply/World Production Capacity and International Distribution Pattern

% of Total Reserves [7]
China: 53
USSR: 12
Canada: 12

Reserves: World 1,800; U.S. 120; "Friendly" 287; 3rd World 201; "Unfriendly" 1,200 [1]

Mine Production: World 1973: 42.66; World Growth Rate 3%/yr ('63-'74); U.S. 3.7875; U.S. % of World 9% [2]
(USSR 19%; China 21%)

U.S. Refining: Yes.

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000: [6]

U.S.	Rest of World	World
0.3	1.4	1.2

U.S. Production/U.S. Demand, Primary Mineral (%): [5]

1950	1960	1970	2000
60.1	58.5	50.0	4.1

Consumption: U.S. 1974^e: 8.059; U.S. % of World Production 1974^e: 18%; U.S. % of World Production (Past) 1970: 23% [2] [1]

Technological Advances: Development of technology to economically recover low grade Tu resources, e.g., Searles Lake, Ca., brines and improved recycling techniques could provide supply required to meet forecast demands. In late '74 a major company announced initiation of mine development and construction in So. Nevada which could increase US production by as much as 25% when full-scale operations begin in mid-'76. [1 & 4]

Capital Investment Problems: Specific problems restricting full development of domestic resources include: difficulty of economically beneficiating and recovering Tu from low-grade ores, high labor costs and high investment costs for plant and equipment. [1]

Environmental Constraints: Minor. [4]

2) Supply/Interruption

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Canada	35	5	46	13
Bolivia	16	6	16	6
Peru	11	2	43	6
Thailand	11	9	12	6
China	-	18	4	5
Korea	-	5	8	3
Australia	-	4	12	3
Portugal	-	3	4	<1
Brazil	-	3	4	<1
Other	27	6	11	4/47%

Cartel Prospects / Embargo / Secondary Conflicts: Unlikely. Given the possibilities for substitution, the existing stockpile levels as well as domestic reserve, it does not appear that the US can be threatened. [12]

3) Demand

New Uses: Nuclear reactor tungsten core research. Carbide usage is strongly increasing. [4]

Substitutions, Functional and Material: Specialty steel: substitute Mo. [1]
Wear resistant applications: substitute Ti, Ta, Ni carbides.

Electric-lamp filaments: substitute fluorescent lighting. [4]

End Use, %: Metal and Construction Machinery, 74; Transportation, 11; Lamps and Lighting, 7; Electrical, 4; Chemicals, 3; Other, 1. [1]

U.S. Consumption Derived from Recycling: 4% (1972) [9]
Good increasability: 20% potential. [7]

U.S. Primary Mineral Demand, Average Annual Growth, %: [5]

1950-1960	1960-1970	1950-1973	1973-2000
5.6	3.6	3.6	4.3

DOD Consumption as % of National Consumption: 8% [15]

METAL: COBALT (1,000 ST metal) **RISK CATEGORY** **DATA SOURCE**

1) Supply/World Production Capacity and International Distribution Pattern

	World	U.S.	Friendly	3rd World	Unfriendly	
Reserves:	2,700(Zaire & Australia)	28 [7]	930	1,169	600^e	[1]

	World	World Growth Rate	U.S.	U.S. % of World	
Mine Production:	1974^e: 29.6	3%/yr ('64-'73) [2]	0 (stopped '71)	0	[1]

U.S. Refining: About 20 refiners and processors were active in 1974. [1]

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000:

U.S.	Rest of World	World	
-	3.2	2.2	[6]

	1950	1960	1970	2000	
U.S. Production/U.S. **Demand, Primary Mineral (%):**	16.0	20.6	4.3	-	[5]

	U.S.	U.S. % of World Production	U.S. % of World Production (Past)	
Consumption:	1974^e: 9.4	1974^e: 31.8%	1967: 31.7% [14]	[1]

Technological Advances: A yield of 5,000 - 10,000 mtpy Co may be expected from deep-sea manganese nodules in the '80s. Bureau of Mines investigating economic methods for beneficiating low grade domestic ore, nickel ores and laterites. [13] [4]

Capital Investment Problems: Increased mining and refining costs: Co prices have increased to \$3.75/lb. [1]

Environmental Constraints: None.

2) **Supply/Interruption**

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Zaire	49	56	32	47
Belgium-Luxembourg	28	-	-	-
Finland	7	5	47	7
Norway	6	-	-	-
Canada	5	8	41	9
Zambia	-	56	42	47
Morocco	-	5	20	3
Australia	-	3	3	4/72%

NOTE: 75% imports in '73 originated in Zaire (30% indirectly from Belgium).

Cartel Prospects
Embargo
Secondary Conflicts

A producer-combine would be ineffective: a) Possibility of increased production in US and friendly countries; b) Co supply is inelastic because it is a byproduct mainly of copper. [12]

3) **Demand**

New Uses: New alloys.

Substitutions, Functional and Material: Nickel can be substituted and vice versa in most applications Co is used in alloys when saving exceeds difference between Ni and the more expensive Co; V, Tu, Cr, Mb, and perhaps other metals in complex alloys may prove equal to or superior to those containing Co. No satisfactory substitutes for Co in carbides or in some tool steels. [4]

End Use, %: Electrical, 29; Transportation (aircraft), 18; Machinery, 20; Paints, 12; Ceramics and Glass, 10; Chemicals, 7; Other, 4. [1]

U.S. Consumption Derived from Recycling: 1%, 1972. [9]

U.S. Primary Mineral Demand, Average Annual Growth, %:

1950-1960	1960-1970	1950-1973	1973-2000	
7.9	4.2	6.6	3.1	[5]

DOD Consumption as % of National Consumption: 13% [15]

NOTE: Cobalt is a byproduct of copper mining.

METAL: HAFNIUM (ST metal) **RISK CATEGORY** **DATA SOURCE**

1) Supply/World Production Capacity and International Distribution Pattern

Reserves:	World	U.S.	Friendly	3rd World	Unfriendly	
	310,000	125,000	70,000	55,000	60,000	[4]
	545,000	same	252,000	108,000	same	[3]

Mine Production: World	World Growth Rate					U.S.	U.S. % of World	
	'69	'70	'71	'72	'73			
1973: 85.	83	90	87	85	85	0	0	[2]

U.S. Refining:
Production: 33 ST, 1971 [3]

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000:

U.S.	Rest of World	World	
10 or more	10 or more	10 or more	[6]

U.S. Production/U.S. Demand, Primary Mineral (%):	1950	1960	1970	2000	
	-	-	-	-	[5]

Consumption: U.S.	U.S. % of World Production	U.S. % of World Production (Past)	
1973: 35	1973: 41%	1969: 34%	[2]

Technological Advances: Better methods for separating Hf from Zr are likely to be developed which could make Hf supply less dependent on Hf-free Zr. [4]

Capital Investment Problems: Hf will be available at reasonable cost as long as there is continuing demand for reactor-grade Zr. [4]

Environmental Constraints: Zr-Ti mining problems. [4]

2) **Supply/Interruption**

Import Sources: [8]

	Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Metal:	France	95	-	-	-
	Japan	2	-	-	-
	West Germany	2	-	-	-
Ore:	Australia	-	1	67	114

Cartel Prospects
Embargo None.
Secondary Conflicts

3) **Demand**

New Uses: Main problem: Lack of commercial uses. [4]

Substitutions, Functional and Material: Many alternate materials are used for control rods in water-cooled nuclear reactors including silver-indium cadmium, boron stainless steel, and rare-earth stainless steel alloys. [4]

End Use, %: Nuclear Reactors (control rods in naval reactors), 85; Ceramics and Glass, 6; Photography, 6; Other, 3. [1]

U.S. Consumption Derived from Recycling: None. [3]

U.S. Primary Mineral Demand, Average Annual Growth, %:

1950-1960	1960-1970	1950-1973	1973-2000	
7.9	4.2	6.6	3.1	[5]

DOD Consumption as % of National Consumption:

METAL: TANTALUM (1,000 ST metal) **RISK CATEGORY** — **DATA SOURCE**

1) Supply/World Production Capacity and International Distribution Pattern

Reserves:	World	U.S.	"Friendly"	3rd World	"Unfriendly"	
	50.5	0	3.5 (Canada)	42.0 (Brazil)	5.0 (USSR)	[3]

Mine Production:	World	World Growth Rate	U.S.	U.S. % of World	
	1973: 1.149	5%/yr ('64-'73)	0	0	[2]

U.S. Refining: Production 1968: greater than 60% of total world Ta production. [4]

Ratio of Recoverable Reserves (at U.S. 1973 Prices) to Cumulative Demand, 1973 - 2000: [6]

U.S.	Rest of World	World
-	2.8	1.2

U.S. Production/U.S. Demand, Primary Mineral (%): 1950 - 1960 - 1970 - 2000 - [5]

	U.S.	U.S. % of World Production	U.S. % of World Production (past)	
Consumption:	1974e: 0.4665	1974e: 41%	1972: 33% [3 & 2]	[1]
	1973: 1.1105	1973: 97%		

Technological Advances: Recently improved extraction techniques have made it profitable to recover Ta from tin slags originating in Malaysia, Thailand, and Nigeria. [4]

Capital Investment Problems: Prices are likely to continue high because of relative scarcity of economic deposits throughout the world. [4]

Environmental Constraints: No problem. Stack exhaust fumes, gases, and dust from processing plants are easily controlled. [4]

2) **Supply/Interruption**

Import Sources: [8]

Country	% 1970-73 [1]	% of World Primary Prod.	% of Country's Prod. Exported to U.S.	% of U.S. Demand Supplied
Australia	28	4	96	7
Canada	23	8	20	2
Zaire	17	3	38	2
Brazil	14	7	46	6
Thailand		41	50	34
Nigeria		19	66	21
Malaysia	-	4	27	2
Mozambique		1	44	1
Other	18	2	100	5/88%

Cartel Prospects
Embargo
Secondary Conflicts } Unlikely.

3) **Demand**

New Uses: Ta-base alloys used increasingly in aerospace and nuclear applications. Most demand growth will probably originate in the electronics area. [13]

Substitutions, Functional and Material: If supply is curtailed and price substantially increased, Al (e.g., capacitator applications), Ni (e.g., high strength steel), Ti, Zr, Cb, Pt, Tu, Re, stainless steel, and glass could be substituted for different uses. [1 & 4]

End Use, %: Electronic Components, 64 (mostly semiconductors); Machinery, 24; Transportation, 10. [1]

U.S. Consumption Derived from Recycling: 12%, 1972. [9]
Ta scrap identification and segregation techniques are not satisfactory and technological improvement in scrap recovery could result in an increasingly important supply source [4]

U.S. Primary Mineral Demand, Average Annual Growth, %: [5]

1950-1960	1960-1970	1950-1973	1973-2000
13.0	8.2	9.9	4.8

DOD Consumption as % of National Consumption: 6% [15]

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